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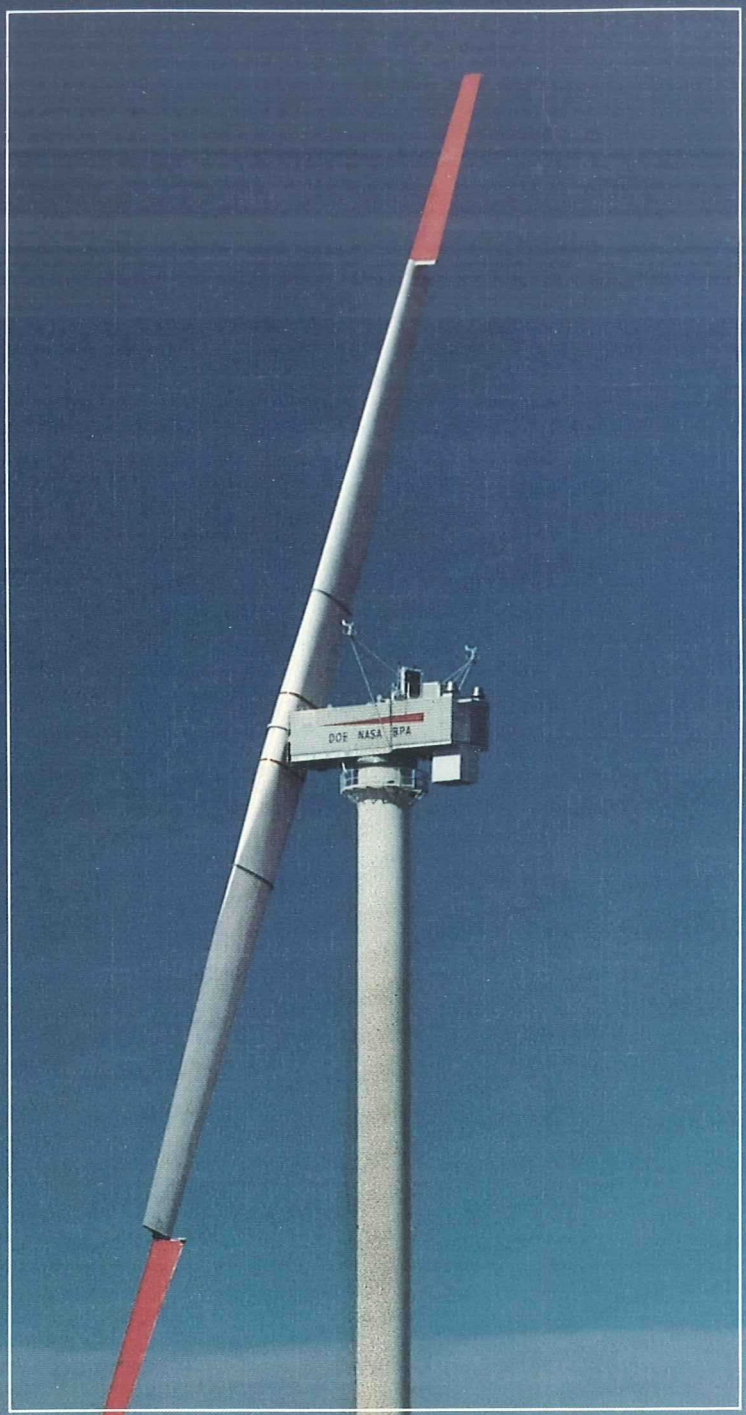

Capturing Energy from the Wind

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NASA SP-455

Capturing Energy from the Wind

James L. Schefter

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Foreword

It is always interesting to observe the application of an old technology to a contemporary problem and to watch the technology evolve from the shakiest of beginnings to assume an independent life of its own. The recent developments in wind power represent a fascinating case of such a technological rebirth. While the lineage of the concept is ancient, only in most recent years have we begun to see that this old idea — a special form of solar energy — is quite capable of making a contribution toward our national goal of energy independence, in a manner that is environmentally benign.

Two characteristics of wind power are beginning to emerge that make it of particular interest to some regions of the world. One is the comparative promptness with which new generating capacity can be brought on line, regardless of the remoteness of the site. This is in stark contrast with the many years required for large thermal, nuclear, or hydroelectric installations. The other characteristic is an increasing awareness of the way in which the somewhat fitful wind can collaborate so efficiently with existing generating systems, using impounded water, for example, as a giant energy storehouse against future needs. If wind power in the years to come earns itself a significant place in our total energy scheme, both of these traits will be important elements in the use of wind turbine generators.

Regardless of how the future unfolds, this volume is valuable as a statement on the present standing of wind power, and a reminder of that old adage that there is nothing new under the sun.

Mark O. Hatfield
Chairman
Senate Committee On Appropriations

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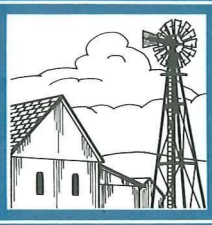

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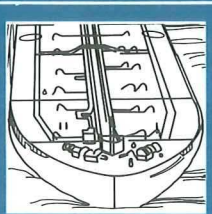

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1
Rebirth of an Ancient Idea

Bigger than anything before, the Mod-1 wind turbine was the first attempt since the machine built in the 1930s and 1940s on Grandpa's Knob in Vermont to produce megawatt power levels from the wind.

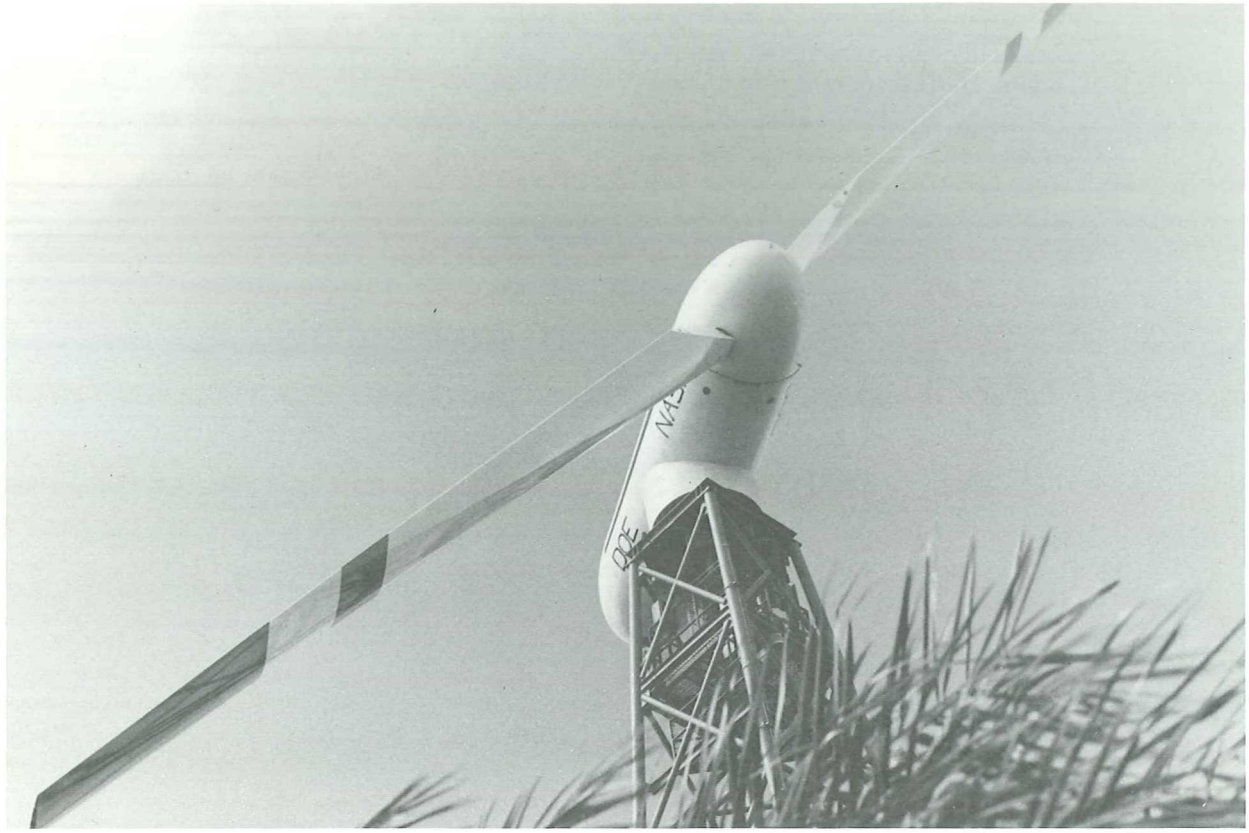
It was one of those cool and humid late summer days in North Carolina, gray without gloom, a moist autumn hint in the air to tell of season's change. The road to Howard's Knob climbed and twisted through the fog. Below and away spread the green hills, and a few houses crouched in landed folds of pastoral beauty. The slightest breeze sent ripples and eddies of gray fog slinking on air. Somewhere in these hills, mythical folk weave nets to catch the wind, and somewhere above, modern magicians turn their technology to the quest for putting wind's power to everyday use.

Around the next bend and up a steep, climbing curve, heavy blue stanchions and girders stood in the mist. They seemed isolated and alone because of fog's camouflage. A little higher up the road, the scene became almost magical, for there pointing down from the fog was the massive red tip of a giant blade. Only the tip descended from the foggy ceiling into clear air.

A breeze puff lifted the gray cotton curtain. There was the tall tower, topped by a boxcar house. There was one enormous metal blade, long and tapered near its end, narrowing sharply into cylindrical roundness before disappearing above into a hub. Momentarily another puff revealed a second blade climbing vertically so high that necks craned to take it in.

This was what the tourist came to see. High on this knob of granite in Boone, North Carolina, where the winds rise at night in response to the random cooling patterns of surrounding mountains and valleys, sat the largest windmill, more accurately a wind turbine, that most people had ever seen. Two steel blades spanned a diameter of 200 feet and the housing for a 2000-kilowatt electrical generator sat some 140 feet above the ground. In the midday mist, with no trace of the 11-m.p.h.

Its design derived from research done in government labs, this giant wind turbine at Medicine Bow, Wyoming can generate up to 2.5 million watts of electricity.



As graceful as a soaring gull, this developmental wind turbine at Oahu, Hawaii, has blades of epoxy-bonded laminated wood. Experience indicates that in this size wood is lighter, cheaper, and more efficient than metal. Near the blade root there are 74 layers of fir, tapering to 8 layers by the tip. Rated power of this Mod 0A machine is 200 kW.

wind needed to begin producing power, the structure sat ghostly silent. Even so, tourists made the trek up Howard's Knob to stare at the future. Then the fog closed in again, enveloping the high blade, the tower, the low blade, until it all faded and disappeared like an apparition.

The fog could cover those tons of steel framework and giant blades. But the time is gone when a fog of indifference can cover the harsh facts of soaring costs and disappearing sources for energy.

The idea of generating electricity with wind power is not new. But the kind of attention that idea is getting today, in terms of research and development, is both new and encouraging to planners looking for renewable energy sources to satisfy growing national demands. The wind turbine at Howard's Knob is just one installation in the Federal wind-energy program administered by the U.S. Department of Energy and managed by the National Aeronautics and Space Administration.

In other parts of the United States and its territories, carefully placed across the country for test and trial of wind power, more giant windmill-like generators stand sentinel to the energy project. Aimed at using one of humankind's oldest energy sources to help solve one of its most modern prob-

In isolated Clayton, N.M., there is strong local pride in the community turbine — even when it's shut down.

lems, the effort is to find reliable and cost-effective ways to harness the wind to produce electricity. In Rhode Island and Hawaii, in Puerto Rico and New Mexico, in Ohio and Colorado and Washington, and in other locales as well, research teams funded both publicly and privately are learning how to turn the wind into electrical power.

But wind machines are not the simple devices they may appear to be and the lessons they teach seldom come easy. Even so, the potential reward to a nation needing more energy from renewable sources may be beyond calculation. Lesser rewards for using wind power have been gathered by civilizations and cultures since early in recorded history.

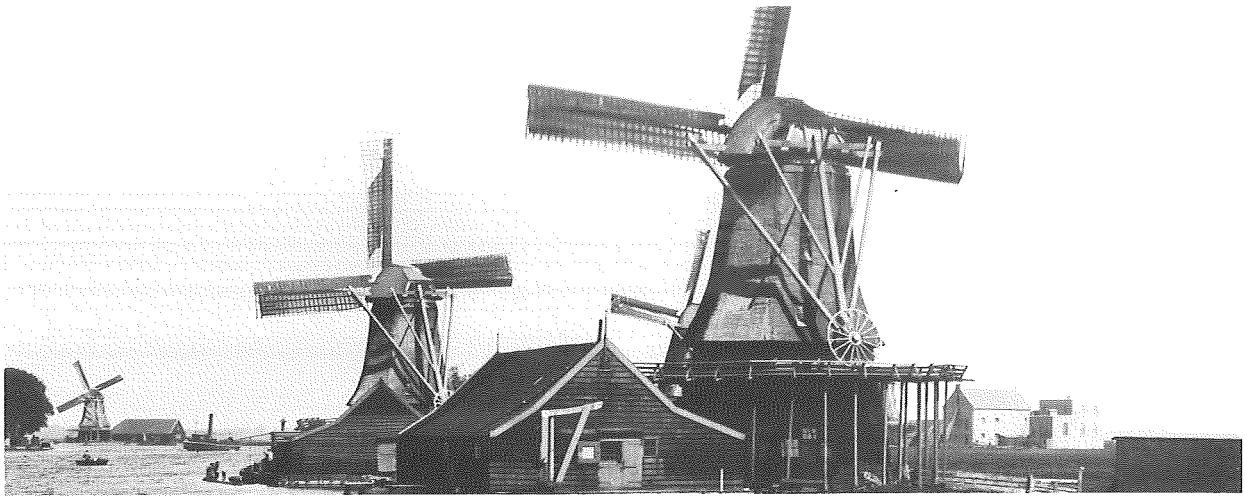
No record survives of the earliest wind machine built by any civilization. It may have been in China more than three thousand years ago. It may have been on the windy plains of Afghanistan. History hints of some sort of wind power used in the Pharaoh's Egypt to draw water for agriculture long before the birth of Christ. Hammurabi may have taken time out from developing a legal code about 2000 B.C. to sponsor development of some sort of wind machine. The earliest confirmed wind machines are in that same region, however, as Persian writers described gardens irrigated through wind-driven water lifts several centuries before the birth of Christ.

But at best, the windmill's true origin can only be guessed at. The Persian machines were horizontal devices, carousel-like contraptions that revolved around a center pole and that caught the wind with bundles of reeds. The carousel is perhaps the simplest design for capturing the wind; it cares nothing for the direction of the breeze, but revolves no matter where on the compass the wind may originate.

From the Middle East, wind-machine technology may have been carried to Europe by returning Crusaders. Accurate records do not exist but soon after the Crusades, windmills appeared in northern Europe and soon were found on the British Isles. It seems obvious that, if ways are seen to reduce the human burden, such ways will quickly spread and be put to use.

To catch the wind at Block Island, R.I., another Mod 0A turbine saves some of the high-cost diesel fuel required to drive the community's generators. This too has worked well, although at first some nearby homes suffered TV-signal disruption.

Windmills flourished, foundered, and came close to extinction, for the wind is a capricious partner. It can be a loyal and faithful worker, pumping water, grinding wheat or pepper or corn, driving a wood saw, or shredding tanning bark. All of those chores, and many more, have been assigned to the wind at mills in Europe and the United States in the past few hundred years. But the wind is not reliable. It can fail to blow just when it is needed the most. It can rage into a gale, forcing mill operators to lock mill blades or let them run free, lest the power of the wind tear apart machinery. It can blow efficiently one hour, then not at all the next, then blow again in no reliable pattern.



Evolving over long periods of cut-and-try design, the Danish, Dutch, and English windmill was developed by carpenter-millwrights with a minimum use of metal. Low-speed torque was good, and although inefficient, the mills were serviceable sources of power for pumping and milling when no real alternatives existed. The tail wheel, which helped absorb thrust, could be "walked around" to take the sails out of the wind. These mills ground grain by a canal near Zaandyk in Holland.

Still, the power of wind, harnessed and directed by machines of many designs, freed the serfs of the Middle Ages from some backbreaking chores. In Holland, the windmill allowed lowland reclamation, pumping water up from land that could be made fertile and productive. In other countries, the growth of wind power meant irrigation, sawing timber, or milling grain. Across the Plains States of America in the last half of the 19th century and long into the 20th, windmills meant the salvation of cattlemen who could drill down to reach water under arid terrain, and then erect wind-driven pumps to fill ponds and tanks for thirsty herds.

If anything came to symbolize wind power for Americans, it was those farm and ranch whirly-gigs spinning on open rangeland or next to the barn. The typical American windmill was far smaller than its European cousin, perhaps only 10 or 20 feet in diameter. The blades were tightly packed into a smooth circle and looking like a child's pinwheel. By the thousands, perhaps by the hundreds of thousands, windmills marched from the Midwest and South through the Great Plains to the Southwest and West, creating oases of green where water spilled around their spindly legs, and extended agriculture and ranching into land previously left in frontier status.

They were sturdy machines. Many stand yet today, the name of their maker still visible in faded paint on the tailvane that kept the blades pointed into the wind. One such windmill stood behind a long-abandoned farmhouse near the Johnson Space Center in Houston until the mid-1970s. Somehow it survived in its derelict condition, and was occasionally tended by a few young people who otherwise concerned themselves with the problems of reaching the Moon. There on some muggy Gulf Coast evenings in 1968 and 1969, it was possible to drive down a pitted dirt path to the windmill and find an Apollo engineer examining a rusted crankshaft or twisting baling wire through pump-arm joints to rejoin sections fallen loose.

Then in the fading light, the rusty wires binding the rotor vanes to the broken wood platform atop the old tower would be pulled free. In a few moments, the evening breeze accepted its familiar assignment; blades creaked noisily around, some wobbling with a floppy rattle, and the ancient windmill regained something of its decades-lost youth. In another minute or two, the coolest and clearest of underground water would begin to trickle from rusted pipes, quenching the thirst of a homebound aerospace technician who still marveled at what the wind could do.

Others came to that creaky windmill spinning almost within sight of the control center that would soon hear about small steps and giant leaps taken on another world. There were the children of

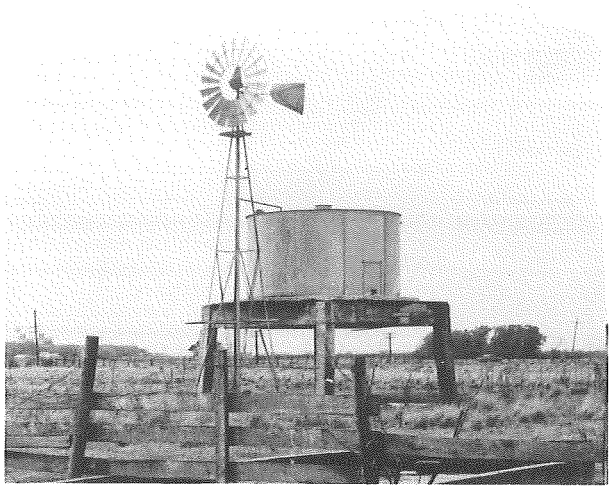
aerospace, growing up with no ready understanding of their high-technology environment. There were geologists from the oil company that owned the land, and the cattle rancher who leased it. There was a journalist who wrote about moons and wandered beneath the wind machine. Some saw the windmill without seeing it at all. And some saw it weakening year after year, and grieved when it ultimately fell to a developer's bulldozer.

Another windmill bites the dust. So what?

The fate of windmills is tied to industrial growth, better machines, and cheap fuel. First the steam engine, and then the internal-combustion engine and electric motor proved so efficient in almost every way that windmills traveled the road from commonplace helper to obsolesence in little more than a historical eyeblink. Why drive mill stones or saw blades with an unfaithful wind when these new engines are smaller, more powerful, and nearly always ready to work? Why lift water with the wind when an electric pump can be had?

For a brief moment in time, no more than three or four decades, windmills seemed to find a limited place in modern society. The Danes developed wind-powered generators in 1890, small units by any standard that could develop up to 25 kilowatts. The little stations by the hundreds helped lead Denmark into the new century, but eventually could not compete in upkeep or convenience with larger and more efficient steam turbo-generators.

A similar fate awaited many American windmills. As rural Americans became enamored with the burgeoning radio networks that relieved dark-hour tedium, small windmill generators by the thousands were installed in the countryside. By the late 1920s, wind power was the common provider of rural electricity, mainly to charge the storage batteries that powered the radios of the day, and

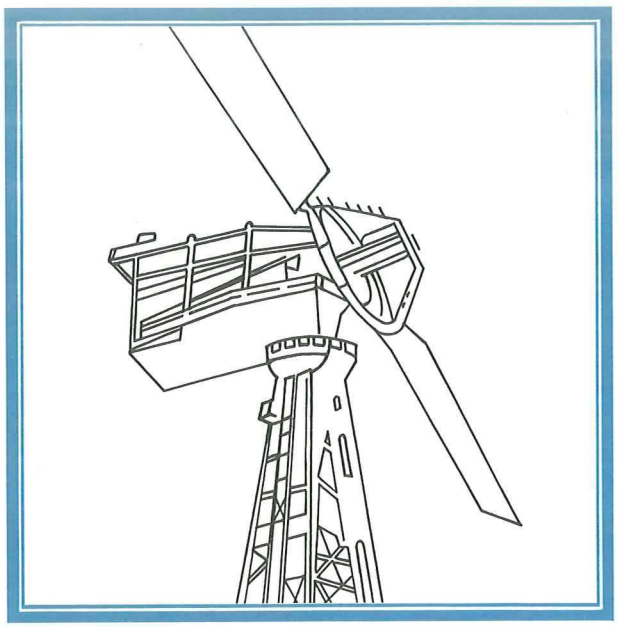


The rural American windmill, developing in the 19th Century and surviving until displaced by rural electrification, was highly practical. A man could order one by mail and erect it himself; a blacksmith could help on any needed repairs. The torque was low and output was in the fractional horsepower range. Pumping water for livestock was the common duty.

the wind-generator industry looked toward a healthy future. Within a few years, the industry was all but dead.

Windmills in America became anachronisms with creation of the Rural Electrification Administration in 1935. Its purpose was to bring cheap power-line electricity to the nation's farms and ranches, and Congress quickly passed funding legislation in 1936 that provided easy and cheap loans for that purpose. Within a few short years, power lines spanned the country, public and private utilities flourished, and an electrified countryside found windmills passe for almost any purpose.

But any reports of the death of wind power were premature. Even forty years ago, the potential of the wind to drive giant turbine generators was being seriously considered. Palmer Putnam did just that in 1939 and pioneered a project that would stand alone in energy annals until the late 1970s. Putnam had a degree from the Massachusetts Institute of Technology. Aghast at the cost of his electric bill (in 1934!), he plunged into an effort to develop a giant wind-turbine generator synchronized with New England utility companies. In that way, power from the wind could be fed into the local utility grid.



A pioneer 40 years ago, the Smith-Putnam wind turbine was the first partially successful effort to extract utility-scale alternating current from the wind. Located on a Vermont hilltop called Grandpa's Knob, it was rated at 1.25 megawatts, and operated intermittently for several years, handicapped by wartime materials shortages. It was a remarkable test machine and, except for escalating costs, could have paved the way for improved versions. Only recently were its records surpassed by turbines using newer materials and processes. A downwind machine with stainless-steel blades sweeping a disk almost 175 feet in diameter, its fascinating history is described in Palmer Putnam's excellent book, "Power from the Wind."

The idea attracted considerable support, including the backing of the S. Morgan Smith Company, and assistance from some of the best technical designers and engineers of the time. In the end, it was the time that did the project fatal damage.

It became known as the Smith-Putnam turbine, a 1250-kilowatt giant that yielded maximum power when wind speeds reached 30 m.p.h. The turbine was turned by two huge airfoil-shaped stainless-steel blades. Together the blades and rotor hub spanned 175 feet, larger than any windmill ever before built. One by one, the problems fell before the technological onslaught until, in 1941, a 110-foot tower took form on Grandpa's Knob, Vermont. Up went the generator and shaft. Up went the huge blades, each 70 feet long, 11 feet wide, 8 tons of stainless steel skin and ribs. In mid-autumn, testing began, and on October 19, 1941, engineers turned the windmill over to a chill 24-m.p.h. wind. The giant blades turned faster and faster, the generator cut in, and wind-produced electricity flowed from the knob into the utility grid. Similar though less ambitious events had occurred in other countries, but for the United States, this was a first, and for the world, it was the most electricity ever generated by a single wind turbine.

Palmer Putnam had long since gone to Washington to help in the war effort. But the Smith-Putnam wind-turbine project continued. The machine generated power until a bearing failed in 1943 and no replacement was available due to wartime priorities. It was to be nearly two years before Grandpa's Knob saw the turbine operate again. When it did, time and long unuse had taken their toll. Tiny cracks had appeared in the blades and in March 1945, shortly after the project started up with a new bearing installed, one blade flew free. That was the end. The Smith Company had put about $1.25 million in company funds into the project. While wind turbines were proved technically feasible, the costs were too much. It would be more than thirty years later, in a time of oil embargoes, skyrocketing inflation, and energy shortage, before a larger turbine would feel the wind in its blades and generate more electricity than the Smith-Putnam machine on Grandpa's Knob.

The energy crisis of the 1970s set into motion a Government search for alternate sources of energy

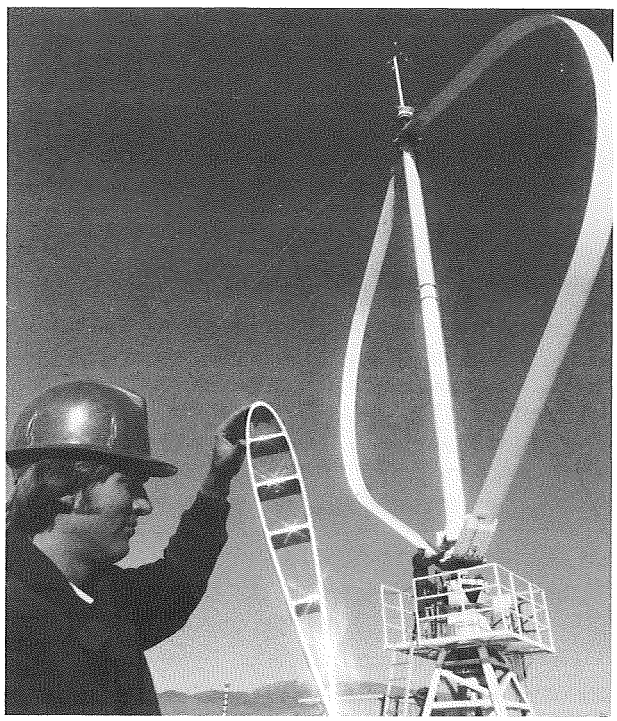
in almost any form. First the National Science Foundation, then the Energy Research and Development Administration, and finally the newly created Department of Energy was charged with prime responsibility in that search, with strong and active development assistance from the National Aeronautics and Space Administration. In addition, private companies ranging from large utilities to small manufacturing concerns are pushing forward in the private sector.

The search for energy sources, if not energy independence, included solar heating and cooling, solar thermal electricity generation, photovoltaic generation, synthetic-fuel development, oil-shale development, geothermal resource recovery, and much more.

And on a scale more massive than any ever attempted, it includes a Federal wind-energy program that began aggressively in 1973 and has already produced significant and heartening results. The Department of Energy (DOE) is overseeing development of wind-power technology ranging from systems generating only a few kilowatts to large machines in the multimegawatt range.

DOE has overseen small-system (less than 100 kilowatts) development and evaluation at its Rocky Flats Wind Energy Test Center near Golden, Colorado. There, on any given day, dozens of small windmills, each different in appearance, each different mechanically and perhaps conceptually, may be turning within easy sight of each other. Instruments record stresses, strains, power output, and other factors that give engineers the data they need to determine efficiencies and value of each system. Some systems are commercially available and are being evaluated. Other systems are under development, also with the goal of improving the technology.

Sandia Laboratories in New Mexico, also a contractor for the Department of Energy, is looking at Darrieus vertical-axis designs and other concepts that could be breakthroughs in wind-power technology. There are double and triple blade designs, eggbeater-shaped blade designs, and others undergoing test and trial. Other innovative



Vertical-axis wind turbines, known in the trade as VAWT's, are indifferent to wind direction, and veering winds do not create yaw loads. Another advantage is that the gearing and generator are accessible and close to the ground. A VAWT drawback is that it is not self-starting; one or more motors are needed to spin it up to the power range. This experimental VAWT, under trial at Sandia, uses extruded aluminum blades of airfoil section, though blades of symmetrical section also work well. The diameter swept by the blades of this machine is 55 feet, and the power fed to utility lines is rated at 60 kilowatts. Target cost of energy is 4 cents a kilowatt hour.

Looking clean and spare against the windy sky, this modern giant barely seems related to the more familiar Dutch and rural U.S. windmills. First-time visitors are likely to be astonished by the size — those blades span the length of a football field — and by the stately slowness of rotation. At full-rated speed, it turns at only 17.5 r.p.m., though even then the blade tips are travelling at speeds approaching 200 m.p.h.

Speed and output are governed by twisting the outermost 45 feet of each blade, shown dark in this photo. A "hard-over" command brings the 90-ton rotor to a stop in less than a minute, typically in about 30 seconds. This Boeing-built machine in Goodnoe Hills, Washington, generates 2.5 megawatts for the Bonneville Power Administration. It is one of three big turbines that are now in operation at this wind farm.

designs are investigated at DOE's Solar Energy Research Institute in Golden, Colorado.

Other research avenues also have direct DOE sponsorship, with studies of the wind itself underway at Pacific Northwest Laboratory and some studies underway through the Department of Agriculture.

Large conventional wind-turbine development is assigned by DOE to the National Aeronautics and Space Administration. With the large turbine program managed by NASA's Lewis Research Center in Cleveland, the agency, by the beginning of 1981, was field-testing turbines ranging from 100 kilowatts to 2.5 megawatts at seven separate sites. At each site, the turbines feed power to local utilities. So encouraging are results of the program that NASA reported in late 1980: "No serious barriers to commercialization have been identified."

It is unlikely that a more positive statement about the future of wind energy could be made today. The outlook is strikingly different from the days of Grandpa's Knob, and from all the other early attempts to harness the wind to electrical generators.

From a serious beginning in the mid-1970s, the nation seems to have made remarkable progress in but a short time. How did it come about? What have we learned about wind turbines?

Answers to the Common Wind-Turbine Questions

Large wind turbines, still unfamiliar to the public, evoke similar questions from first-time viewers. Here are answers to the ten questions most often asked of engineers.—Robert A. Wasel.

What happens if lightning strikes?

Designers assume that blades will be struck by lightning. With metal blades, the charge is conducted safely along the blade to the tower and to the ground. If the blade is constructed of laminated wood or fiberglass, special conducting paths are included along the length of the blade. Those in use include strips of aluminum or aluminum screening just below the surface of the blade.

Are wind turbines quiet or noisy?

Very little noise is normally generated except close to the machine, where there is the swishing sound of the blades moving through the air. Background wind noise masks this a short distance away. There have been cases in which turbulence in the wake of the tower has caused the blades to make thumping noises each time they passed the tower. This is avoided in upwind configurations.

Are they complex? Do they need much maintenance?

They are basically simple, with a rotor driving a generator, usually through a flexible coupling and step-up gearing. There is moderate complexity in control systems with their sensors, computers, and hydraulics. Production machines should run 30 years with the maintenance normal for large machines.

What keeps them pointed properly?

While small machines can use a weathervane tail, most large machines are mechanically pointed. A small vane on or near the machine closely follows wind movement, sending direction signals to a computer that defines a moving average. When this differs significantly from wind-turbine alignment, a drive mechanism turns it into the wind.

Why don't big turbines have more blades?

A two-bladed propeller-type rotor, operating at a tip speed of 100 to 200 m.p.h., comes close to maximum theoretical efficiency. A third or fourth blade could increase efficiency slightly, but not in proportion to the added cost and weight.

How do you stop the blades? Is there a brake?

For large machines, the blades (or portions of the blades) are feathered or twisted about their long axis until rotation stops. It is also possible for the entire machine to be turned until the blades do not face the wind. Friction brakes could be used, but on large machines an impractically large amount of heat energy would have to be dissipated.

Is an operator on duty in the nacelle?

No. Large wind turbines are designed for remote operation. There are auxiliary controls in the nacelle and in or near the base of the tower for tests or emergencies. But normal procedures are to control large machines remotely from a utility power-control center.

Are ice storms a serious threat?

They can be. Ice accumulating on blades can be a hazard by interfering with control-surface operation or by causing imbalance, or by exposing surroundings to slung ice fragments. Ice-detection sensors to trigger machine shutdown are part of most large wind-turbine designs.

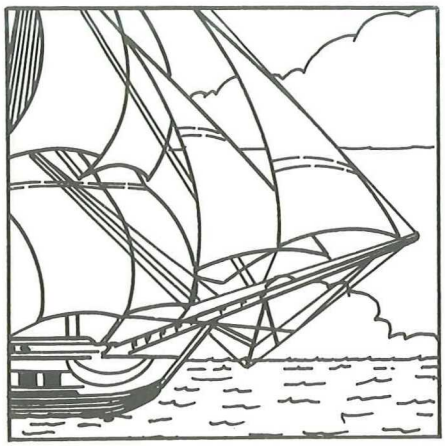
Why do blades on big machines turn so slowly?

Blades on big machines have an airfoil shape, and are most efficient when they move through the air at six to ten times wind speed. To get full power in a 25-m.p.h. wind, blade tips should have a speed of 150 to 250 m.p.h. The larger the turbine, the longer the blades and the slower they turn to reach this tip speed. On the Mod-2 turbine, the 300-foot blades turn at only 17.5 r.p.m. to have an 190 m.p.h. tip speed.

Do the big blades injure birds?

The risk to birds was viewed as a potential problem in early studies, but experience and careful observation to date show that birds have no difficulty in avoiding turbine blades. A contributing factor is the low rate of rotation, usually below 40 r.p.m.

2
The Learning Tools



The sailing vessel is by far the oldest and most widespread application of wind power, its origins lost in the beginnings of civilization. By the time steam overtook it in the 19th Century, sail had achieved a high degree of sophistication.

To poets and many a small-boat skipper, the wind is a capricious and invisible spirit. To a geophysicist, however, wind is better understood. It is air in motion, and it moves because of uneven heating of the surface of the Earth. Thus the kinetic energy of the wind is solar energy. Since the Earth's surface is not uniform, incoming solar energy is received and reradiated in different ways. Some surfaces absorb more heat than others, creating pressure and density differences that force the air to move from one place to another. Land and water absorb heat differently, for example, as do mountains and valleys, and this generates breezes.

When you enlarge your view to a planetwide perspective, the picture grows more intricate. The Earth's atmosphere is a complicated mechanism that operates on many scales of time and place. The tropical regions receive an excess of heat, compared to their average annual heat balance, whereas the polar regions have a deficit. Since the tropics don't get hotter from year to year and the poles don't get colder and colder, there is obviously an exchange of heat energy between latitudes. This doesn't occur directly between the poles and equator, for the Earth rotates daily on its axis, toasting on a tilted spit. Together the combination of diurnal rotation and differential heating create great planetary circulation patterns, the westerlies and the trade winds, the large airstreams that usually take the shape of major undulating waves traveling much of the globe. Superimposed on these are smaller waves or perturbations, the fronts and atmospheric instabilities that cause day-to-day weather changes at particular locations. The two kinds of waves, aided somewhat by ocean currents, carry out the heat transfer between equator and poles.

How the wind blows at a particular place is also affected by the distribution of land and water sur-

Inside a welded steel tower, looking up, one can grasp the scale of big wind turbines. Such towers are light, strong, aerodynamically clean, and quickly erected by a skilled crew.

The giant size of big modern wind turbines is masked by their slimness and simplicity of line, but the rotor on this Mod 2 machine is 300 feet from tip to tip. The hub atop this welded steel tower is 200 feet above the ground. Viewers are often surprised by the seeming slowness of rotation, 17.5 r.p.m. for this machine. A step-up gear ratio of 103 to 1 spins the generator shaft at 1800 r.p.m. This 2.5-MW turbine is one of three installed at Goodnoe Hills in southern Washington that feed power to the Bonneville Power Administration. Power begins in winds as light as 14 m.p.h. at hub height.

faces, and by the distribution and topography of land masses. Effects may be of a local character, generating breezes with a duration of hours, but they may also be of a hemispheric scale, with a duration of months, as with monsoons. Wind varies considerably by season, and in the temperate latitudes the strongest winds generally occur in winter and spring, as with Masefield's dirty British coaster with the salt-caked smokestack:

"Butting through the Channel in the mad March gales . . ."

While it is immaterial to a wind turbine whether the breeze striking its blades is a local or a hemispheric phenomenon, the distinction can be important to an engineer concerned with maximizing annual energy output. He cares less about gales in the stratosphere than about what blows in a narrow band fairly close to the ground—up to about 200 meters above the surface—even though here it is most prone to the turbulence, vertical shear, and gusting that can stress his machine. It is here that he must capture the wind's kinetic energy for useful work. For millenia this capture has been managed by sailing vessels and simple windmills, but it is only in the last handful of years that WECS—wind-energy conversion systems—have shown promise of generating significant amounts of electricity. Intensive research and development efforts were begun in the mid-1970s by the U.S. Department of Energy (then the Energy Research and Development Administration), working with the National Aeronautics and Space Administration, other Government agencies, and private industry. In barely half a decade, the Federal wind-energy program has moved from tentative investigation of wind potential to aggressive pursuit of economical and reliable wind-energy conversion systems. The program covers a full spectrum of research:

- Large wind turbines, machines with output above 100 kilowatts, are being developed and field-tested by NASA and a variety of industrial contractors. The program has produced the world's

largest experimental wind turbines and is generating electricity for the power grids of utility companies in half a dozen locations.

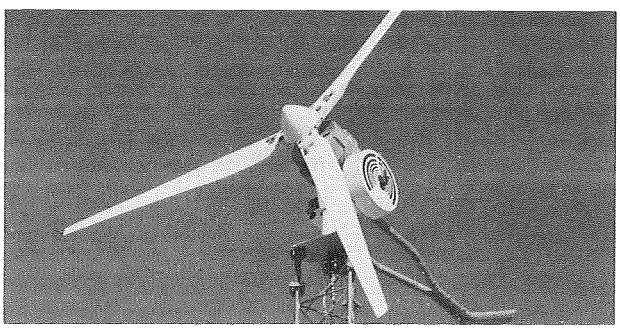
• Small wind turbines, machines generating less than 100 kilowatts, are being developed under DOE sponsorship at the Rocky Flats, Colorado, Small Wind Systems Test Center. In addition to supporting the design, fabrication, and testing of new small turbine systems, the center has tested and evaluated commercial turbines.

• Mid-size wind turbines are under development by both NASA and DOE, with NASA overseeing work on conventional horizontal-axis systems while Sandia Laboratory proceeds with development of the large vertical-axis Darrieus (eggbeater-type) rotors. (Horizontal-axis turbines are the most familiar, with rotors spinning a central shaft parallel to the ground. Vertical-axis machines sweep out a spheroidal-shaped pattern, are insensitive to wind direction, and transmit torque through a vertical shaft, gearbox, and generator near the ground. Each system has advantages and proponents.)

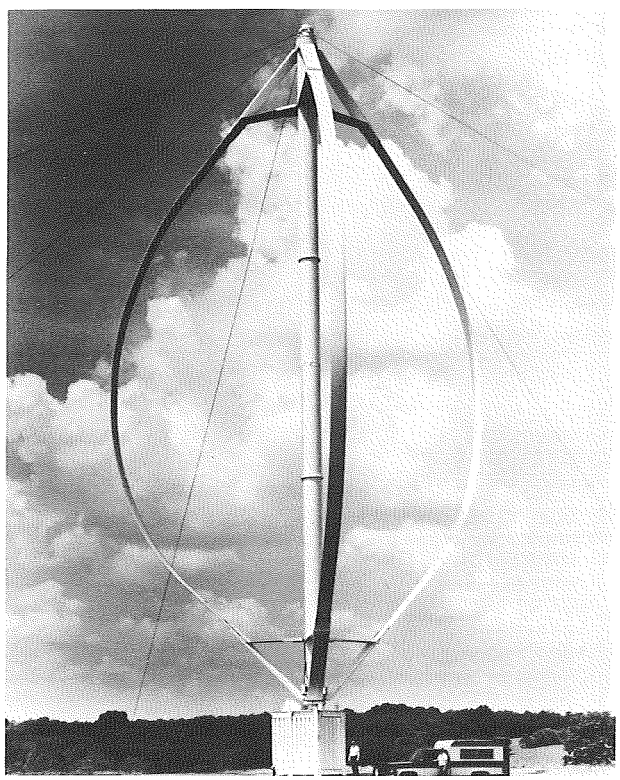
• Innovative wind-turbine systems are studied by the Solar Energy Research Institute (SERI), a research facility operated for DOE at Golden, Colorado. SERI's charter in the wind-turbine area is aimed at analyzing system performance and disseminating information.

• Working under DOE supervision, Battelle's Pacific Northwest Laboratory has made significant strides in developing both a national wind data base and systematic ways to identify and select appropriate wind-turbine sites.

The power potential of wind is considerable. At 10 m.p.h., a breeze that feels comfortable and refreshing to most people, the air passing through a single square foot of area carries the energy equivalent of 10 watts of electricity. The side of a house, or even better, a barn, could intercept enough wind to supply all the electricity a normal



Rated at 2 kW in a 20 m.p.h. wind, this machine employs a torsion spring beside the generator. In overload winds it tilts the 5-m rotor upward and on its back for protection.

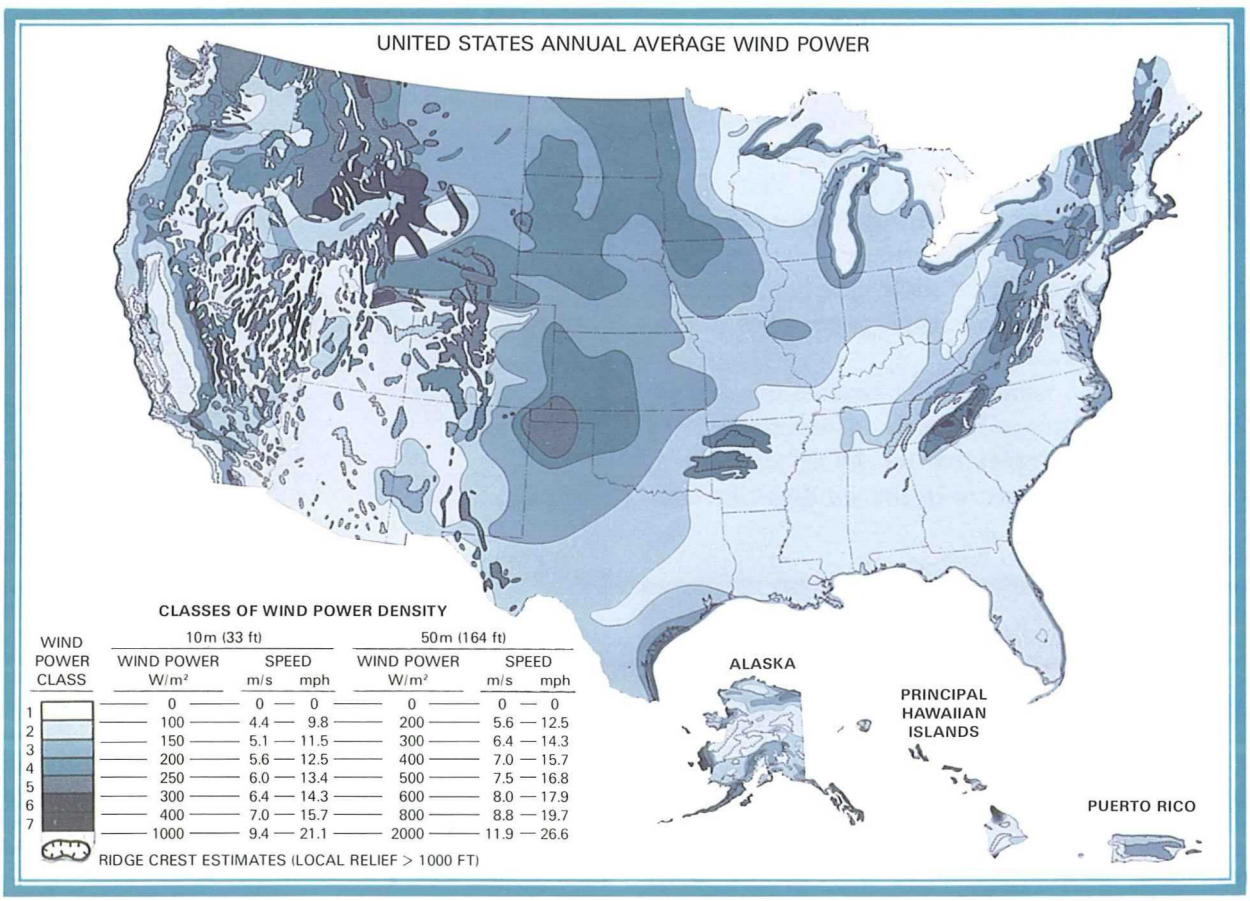


An experimental vertical-axis wind turbine, rated at delivering up to 500 kW in winds of 35 m.p.h. It needs external power to set the airfoil blades spinning at start-up.

family uses. It sounds too good to be true—free energy, just waiting to be harvested and used.

And it is too good to be true. The theory is sound. The practice is considerably more complex, involving aerodynamics, mechanical and electrical limitations, energy lost to friction, size and shape of turbine blades, even the wind itself. Wind may howl one day, sigh the next. It may blow for days at speeds just under that needed for turbine blades to deliver useful power, and then perform for more days in a gusty and perverse fashion. As if all that isn't enough, there are questions—political, environmental, land use, esthetic, noise, television interference, zoning, and purely economic questions to be resolved every time a wind turbine is planned. If not for the significant potential benefits of chasing the wind, of developing practical, productive wind-energy conversion systems, it might seem to be just too much work for too little result. But it is worth the effort.

Studies carried out to give the wind-energy program an accurate look at expected wind conditions in the United States are revealing. Darrell Baldwin, deputy manager of the large wind-turbine pro-



Where the average winds blow best can be seen on an atlas from which this map is taken, prepared by Pacific Northwest Laboratories for DOE. Local terrain features can make such a big difference that detailed anemometer measurements are desirable before final site selection. Access by large cranes for erection and maintenance is another site consideration.

gram at NASA's Lewis Research Center in Cleveland, Ohio, reported in 1980 that theoretically nearly 40 percent of the country has average winds strong enough to make electricity generation attractive. Of the nation's more than 3.6 million square miles, Baldwin said, about 1.6 million experience acceptable average winds.

Most of that land lies west of a line drawn from Grand Forks, North Dakota, to Dallas, Texas. The remainder is concentrated in the northeast, midsouth, and West Coast, Hawaiian, and Caribbean areas. When terrain, land use, and local population considerations are factored in, the area actually available for deploying wind machines drops to about 214 000 square miles. Of that, 157 000 square miles is rated "moderate," with annual average winds of 7–11 m.p.h. Another 54 000 square miles are rated "good," at 11–14 m.p.h. annual wind averages. Only 3000 square miles get an "excellent" rating—above 14 m.p.h.

What does that mean in terms of wind-turbine deployment? Baldwin says that theoretically it is ample land to deploy 340 800 large wind machines similar to the largest now being tested by NASA and DOE. That number is based on turbines spaced at 1500-foot intervals.

That large machine, called the Mod 2, has a rated output of 2.5 megawatts. Most of the time, it puts out less, but the crucial factor is how much electricity a machine generates in one year, not what it does in any particular hour. With maximum deployment of wind turbines, Baldwin sees the potential for wind to produce eventually as much electricity as is now being produced by hydroelectric plants, which is about 13 percent of the electricity now being generated.

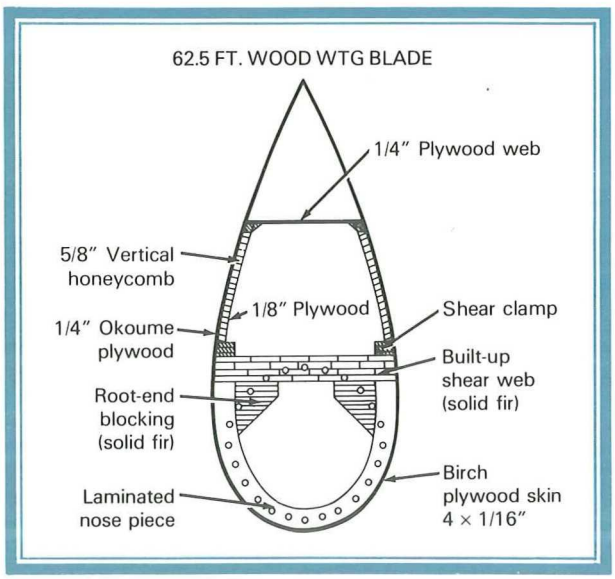
"There appear to be no serious technical barriers to the commercialization of wind energy," Baldwin reported. "All assessments have concluded that it is the most advanced solar electric technology from a cost-effective standpoint." But that doesn't mean that all problems are resolved, that nothing remains to be done, or that the nation can

The massive 90-ton rotor of a Mod 2 machine is wholly controlled by steerable tips extending for 45 feet on each blade. Hydraulic pressure rotates the tips from full stall, shown above, up to rated power at wind speed of 27 m.p.h. and above. Tip control, developed on the Mod 0 machine at Plum Brook, is lighter and simpler than feathering the whole blade.

wake up tomorrow morning to discover that its morning toast is being browned by electricity that began with some distant wind.

There is an abundance of energy in the lightest breeze. But it is virtually non-extractable because no known wind turbine will operate efficiently in very light airs. Similarly the energy carried by high-velocity winds, hurricanes and gales, is obvious to all. But that energy is so potent that even the best of wind turbines aren't designed to withstand its destructive force; they must be shut down. Stormy winds must simply dissipate their energy without contributing to any turbine system.

The practical limits of wind-energy conversion systems are set by a combination of natural physical and mechanical laws. Those laws, and the mathematics through which they are expressed, are thoroughly understood by the engineers involved in the nation's various wind-energy projects. Wind-energy development is not a matter of solving a scientific puzzle; it is a matter of careful planning, careful research, and experimentation to find the right combination of size, shape, materials, and location that will produce the most electricity for the least cost.



There is more than meets the eye to a modern turbine blade. Steel, aluminum alloys, plastics, composites, and laminated wood have all been tried in various combinations, with careful examination for stress fatigue and weathering. The tips of long blades must travel great distances at high speeds in all kinds of weather, including heavy rain and hail, without losing their calculated aerodynamic shape.

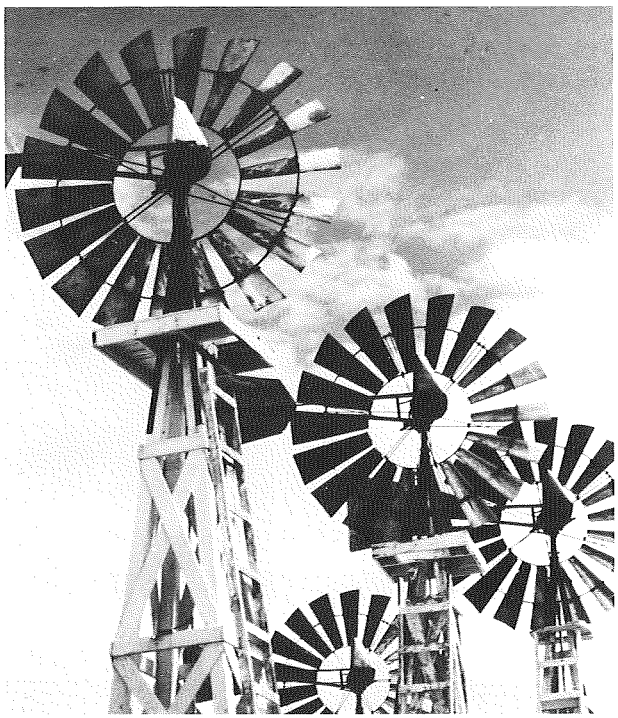
More important, there is no single answer to the quest. Rather, there are thousands of answers, all acceptable, all appropriate. A major goal of the wind-energy programs underway in the 1980s is to find as many of those answers as practical and to make it easier for private industry to find the rest.

But finding those answers involves tradeoffs and concessions. Only a fraction of the energy contained in a given stream of wind, that fraction defined by the power coefficient, can be harvested. The power coefficient depends largely on the size and shape of the turbine rotor—the blades—being turned by the flowing wind. But there is a limit. Called the Betz coefficient, after the man who did the analytical and theoretical work leading to its formulation, it indicates that an ideal propeller or rotor can capture only 59.3 percent of the energy in a wind-stream tube the diameter of the rotor.

Even that natural limit has never been reached. No one has built a perfect rotor. But enough rotors have been built through the years to provide a broad base of data. Experience shows that the ratio between tip speed of the blade and the free-flow wind speed is a major indicator of efficiency. The typical rotor found on most American farm windmills, for instance, has many blades, a small diameter, and spins at relatively low r.p.m. The result is a turbine with significant energy loss from

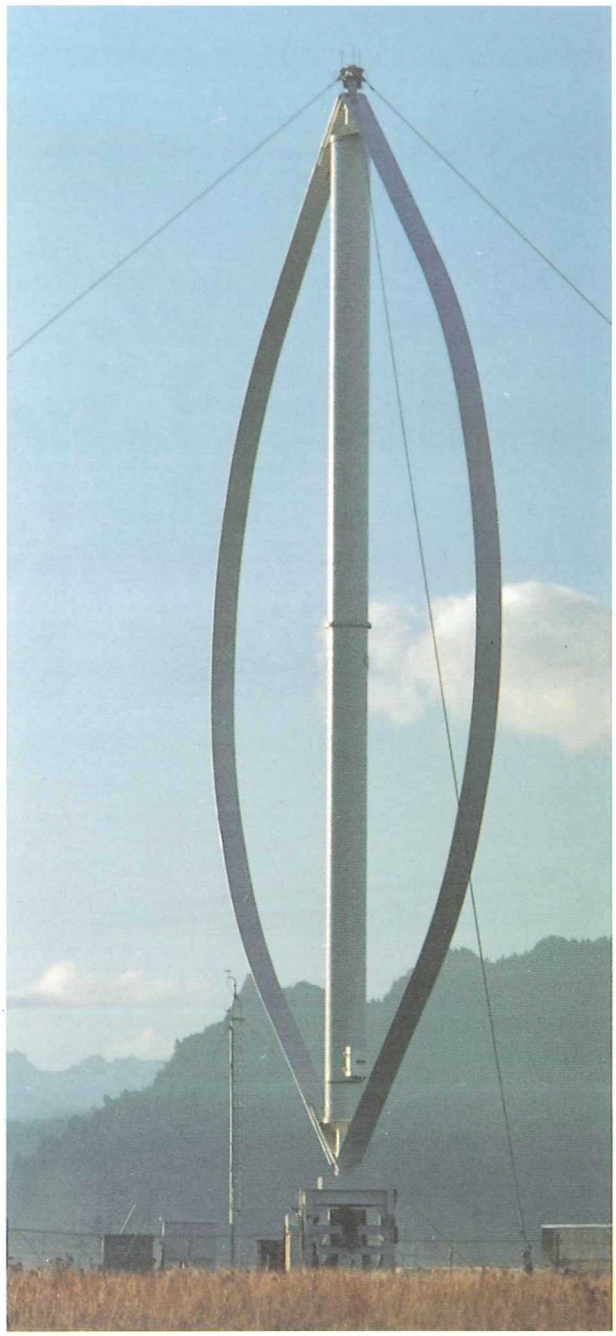
drag, and a tip-speed to wind-speed ratio that barely surpasses unity. Such turbines develop a maximum power coefficient of about 0.3 and fall off rapidly in efficiency as tip speed increases.

The large paddle-wheel blade favored in Dutch windmills is only slightly better. But because of a much larger diameter, Dutch mills reach their peak power coefficient of about 0.17 at higher wind speeds and a tip-speed to wind-speed ratio of about 2.5.



Now vanishing though a few are still at work, the windmill water pumpers were once common across the American landscape. The seven shown at right pumped water into a 36 000-gal. cistern for as many as 1350 cattle near Scottsbluff, Neb. They were in effect the fractional-horsepower motors of an era without electrification for such chores.

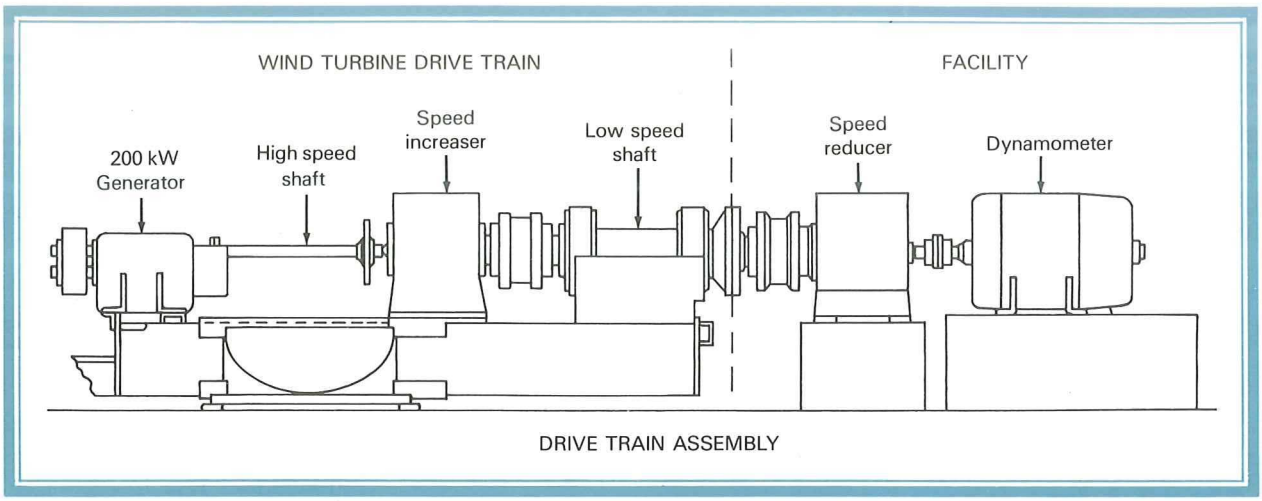
Though now thought of as native to Holland, the classic European mills were also developed by craftsmen in Denmark and England. Earliest was the post mill, in which the entire structure could be rotated to face the wind. Later versions like the one below pointed only a cap on the building.



Two vertical-axis machines, Savonius and Darrieus; develop relatively high power coefficients. The Savonius rotor, designed with a central rotor positioned vertically and curved in a sine-wave approximation to catch any wind, can yield a power coefficient over 0.15 but its efficiency falls off rapidly even before tip speed equals wind speed. And at higher wind speeds, the Savonius is markedly inefficient. The Darrieus rotor is not by itself self-starting and does not begin to produce power until its tip-speed to wind-speed ratio is about 4.2. Then it quickly builds up to a creditable 0.4 power coefficient, which it holds at ratios up to about 6.

Two-bladed horizontal-axis turbines developed by NASA also have maximum power coefficients over 0.4. But when real power output is examined, the power coefficient is only one of the factors to be considered. NASA's early Mod 0 wind turbine, a test-bed machine installed at the Plum Brook facility near Sandusky, Ohio, could theoretically have produced nearly 5 megawatts (5000 kilowatts) of power if allowed to operate in a 60-m.p.h. wind. Instead it produced 100 kilowatts. It also produced 100 kilowatts in an 18-m.p.h. wind, a 30-m.p.h. wind, and every other wind speed up to 40 m.p.h. (measured at hub height), at which it is shut down.

In vertical-axis wind turbines like the Darrieus machine at the left, the convenient accessibility of generating equipment near to the ground is an advantage, as is the machines' indifference to veering winds and to turbulence. Balancing this is the drawback of needing auxiliary power to spin the rotor up to a rate where power can be drawn without stalling the machine. (Upper limit to speed is effectively established by the decreasing effectiveness of the curved airfoils.) The most efficient blade shape and curvature, and the best-performing control systems, are both under engineering development at present.

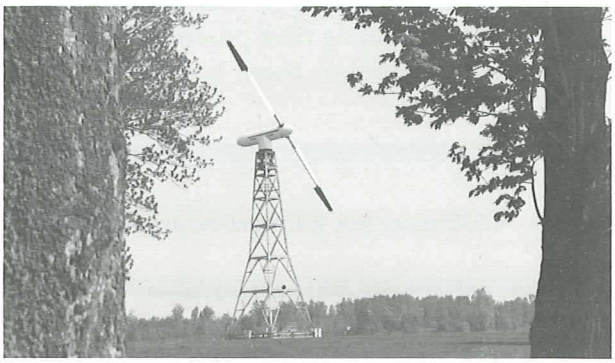


A test rig to check out wind-turbine power trains is shown in this diagram; elements to the left of the dotted line are typical of the machine itself. The step-up gear ratio is often quite large, and a hydraulic coupling may be used to level off the transient loadings imposed by sudden wind gusts.

Why? Because it wouldn't be cost-effective to build a drive train to cope with infrequent high winds.

"The systems we've developed use synchronous alternating-current generators to feed power smoothly into the local utility grid," said Ron Thomas, NASA's program manager for large wind-turbine development at nearby Lewis Research Center, "and that means bringing the generator up to its rated power, and then holding it there by controlling the pitch angle of the turbine blades."

Turbine power is controlled by varying blade pitch—twisting it into or out of the windstream. Depending on design, the entire blade, or just its tip, may be controlled. The blade can be stopped completely by feathering it, or turning it edge-on into the wind until the opposing forces cause it to stall. By maintaining the blade at a constant speed, the alternating-current generator can be precisely synchronized with the local power grid. The result is a flow of electricity that fits in with the frequency that is already prevailing in the grid.



The grandfather test site for modern wind-turbine experiments, the Mod 0 turbine at Plum Brook, Ohio, is a much-reworked 100 kW machine here shown after the turbulence-causing tower stairs were removed. Rotor blade tip control was one of many developments tried out on this experimental machine.

Using constant-speed rotors and generators with maximum output ratings also affects costs—both development and production. Capital expenditures are significantly lower because stresses on materials are reduced, equipment can be designed to operate over a limited range of conditions, and the control electronics required for the system can be somewhat less sophisticated. Any cost-saver that can be built into a wind-turbine machine from the beginning ultimately yields a lower price for electricity generated.

The people closest to wind-turbine development programs have learned an important fact: The cost of electricity produced by a rugged and reliable wind turbine, more than its total energy output, is the major measure of its success.

So important is that factor that a predetermined cost-of-energy (COE) goal is written into every wind-turbine development contract. The Department of Energy and NASA have adopted a standard formula in determining that cost.

The formula is similar to that used by private utilities in determining their production cost, with one notable exception: there is no provision for fuel costs. The fuel is the wind, and the only arrangement like it now in routine use anywhere in the world is the water stored up behind dams for hydroelectric power.

''O&M'' is the annual cost for operations and maintenance.

The fixed charge rate includes factors any business must consider in long-range financial planning. Among them are the cost of borrowing money, taxes, inflation, the design life of the system, and profit. Desired profit can be included in a precise fashion and system design life nearly so. The other factors can be calculated when each year's books are closed.

A thirty-year goal for system design life is included in all wind-turbine development programs. Finally, the formula recognizes that wind turbines today are in the research and development phase, with necessarily higher production costs. Thus the ''system capital cost'' used is not the actual cost of the present experimental turbines, but the projected cost of the 100th production unit. That number gives utilities a better estimate of energy cost, should large numbers of wind turbines be deployed.

''The important thing to remember is that wind turbines will be used primarily as fuel savers,'' Darrell Baldwin emphasized. ''That means that the cost of wind energy must be competitive with the cost of fuel used to produce energy. If it's not competitive, why do it?''

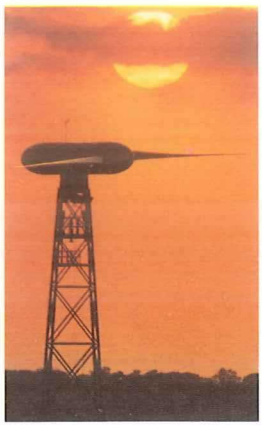
$$\text{COE (cost per kilowatt-hour)} = \frac{(\text{System Capital Cost})\,(\text{Fixed Charge Rate}) + (\text{O\&M})}{(\text{Annual Energy in kilowatt-hours})}$$

With cost-of-energy the major driving factor in wind-turbine development, both DOE and NASA reported encouraging results through 1980. Fossil fuel costs alone continued to increase dramatically, with utilities paying from 1.7 cents to about 4.3 cents in fuel costs to generate 1 kilowatt-hour of electricity. Assuming a moderate fuel inflation factor of 6 percent annually, utilities can expect fuel costs exceeding 7 cents per kilowatt-hour after the turn of the century.

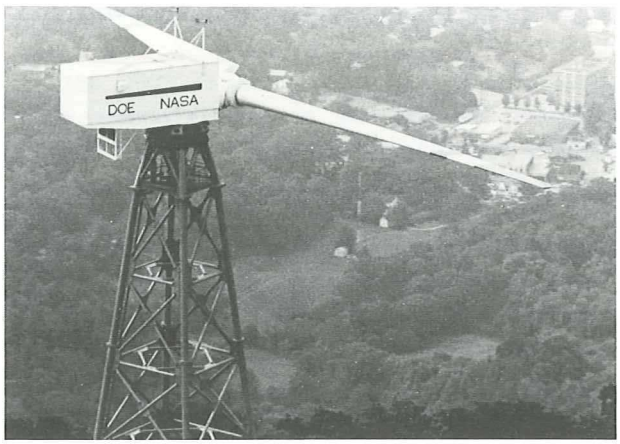
The wind-energy cost goal for large turbines, in contrast, is 4 cents per kilowatt-hour in 1980 dollars, rising to 5 cents by the year 2010.

''Those goals look reasonable,'' according to Baldwin. ''We're not finding any unpleasant surprises to change them.''

Instead, the cost-of-energy trend for large turbines has pointed steadily downward. NASA data



Hovering feathered over Block Island, this 200 kW plant has been among the most successful early-generation turbines. Except for initial TV interference, almost everyone in the small community liked it.



At Boone, N.C., an ambitious increase to a 2-MW turbine wasn't without problems. The worst was an intermittent downwind thumping vibration that strummed on local nerves. Extensive redesign succeeded in greatly reducing the annoying low-frequency noise.

One of three giant 2.5-MW turbines at Goodnoe Hills, Washington, looms high on its windy site. Its welded steel shell tower needs no external bracing. Maintenance men ride up the 200 feet to the nacelle on a small elevator suspended inside the tower.

on its three developmental turbine systems deployed by early 1981—MOD 0A, MOD 1, and MOD 2, each larger than its predecessor—verify the fact. Four MOD 0A machines, wind turbines with rated outputs of 200 kilowatts, have yielded a COE of between 30 and 35 cents. The multimegawatt MOD 1 turbine design could demonstrate a 15-cent COE, while the second generation MOD 2 turbines, rated at 2.5 megawatts, has a COE goal of about 5 cents in 1980 dollars.

"There is a limited market for large turbines with a COE of 4 to 6 cents," Baldwin predicted. "But that market is substantial when you get below 4 cents."

A COE below 4 cents, in 1980 dollars, is the goal for the advanced MOD 5 wind turbines that were conceived for possible deployment in 1983. At that level, utilities would be likely to show markedly stronger interest in wind energy.

But reaching that level depends on more than development of superior hardware. It depends equally on finding the right sites. Battelle's Pacific Northwest Laboratory operates the Wind Characteristics Program Element (WCPE) for DOE, with direct responsibility for accomplishing wind-energy research. The program has four goals: (1) defining the wind-energy resource, (2) developing effective siting technologies, (3) providing information on wind structure and turbulence to designers, and (4) investigating wind-forecasting techniques that would improve the integration of wind turbines into existing power grids.

To officials currently concerned with getting wind-turbine systems deployed for long-term eval-

uation, the first two goals are crucial. In a 1980 report, PNL defined resource assessment in terms of "large-scale analysis of the wind energy resource by estimating the wind energy potential of a given area and the distribution of wind energy within that area. In siting, wind characteristics are analyzed on a much smaller scale. The objective of siting is to define the precise location for a machine or cluster of machines."

Early wind assessments at the national level yielded some conflicting data, and PNL reexamined the studies to recommend changes. "On a regional scale, a wind resource assessment is improved most significantly by simply including more data in the analysis," PNL reported. The laboratory then took on the task of reassessing the five-state Northwest Region to find methods of improving data. Researchers devised a wind atlas with grid sectors of 15 by 20 miles. They then selected a large number of weather stations reporting hourly or three-hourly data to the National Climatic Center. Combined with proven estimation techniques for areas lacking reporting stations, the PNL wind experts developed a vastly improved procedure for assessing regional winds. The wind power atlas they developed has now been expanded to cover all parts of the United States.

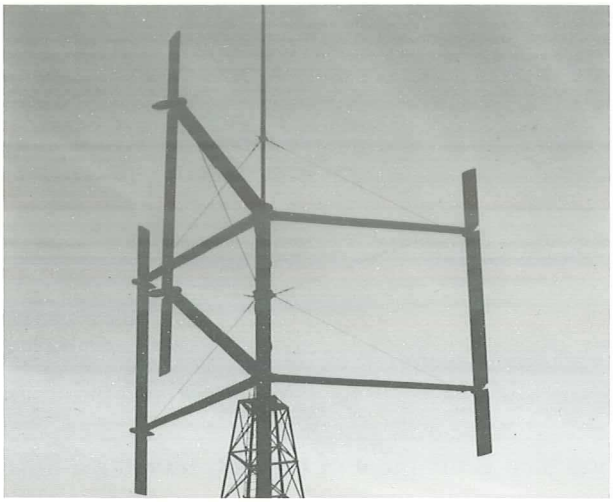
The team also developed a recommended strategy for use by large public utilities seeking to deploy 10 to 50 multimegawatt wind turbines. They reported:

"The strategy is conservative, partly because the large-scale generation of electricity by wind turbine generators is a developing technology. It is assumed that wind characteristics at a site will have to be thoroughly documented, because the nature of the wind at the site not only governs the energy output of the cluster, but also affects the service life of the wind equipment and both scheduled and unscheduled maintenance costs. Perhaps with experience, the site selection process can be simplified. Certain steps may be found unnecessary, or requirements on the quantity and quality of wind data collected at each step may be decreased. . . . Extensive measurements cost a great deal to make and to interpret, but the cost of wind-generated electricity is very sensitive to wind characteristics at a site. A simple analysis shows that siting expenditures of $50 per installed kilowatt or more may be justified."

Detailed procedures, including suggested formulas for refining calculations on the energy available from any particular wind-turbine site, are available to interested parties. But the PNL research group continues to look for feedback from users. "[These] recommendations are based on theorizing," the researchers said in 1980, "since no one has sufficient experience to speak with authority on this subject. Still, large utility-sized machines are now being produced and will have to be sited. Experience with these initial installations will be critical in evaluating current siting approaches and in defining the crucial characteristics of a good wind turbine site."

Another crucial factor in wind-turbine deployment, examined in greater detail later, is the interface between wind turbines and the local power grid. Some initial study on potential problems has been completed for the Electric Power Research Institute (EPRI) of Palo Alto, California. In one late 1980 report, EPRI and its investigating team stressed that small utilities may face the most serious questions.

"Dynamics problems may limit the ultimate penetration of wind turbines into utility systems," EPRI reported. "This penetration limitation is more likely to exist for small, isolated utility systems than for large interconnected systems in



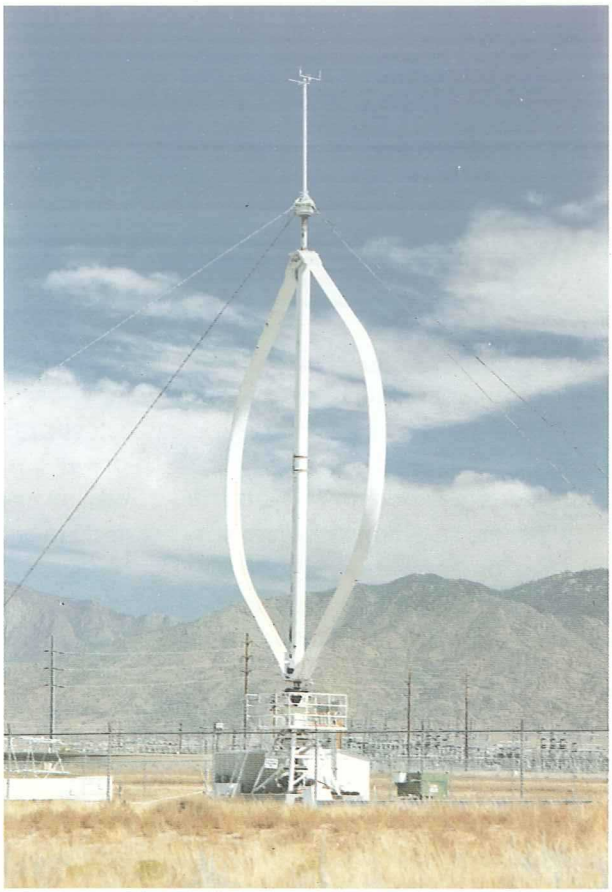
The Giromill, developed by McDonnell-Douglas, is shown on test at Rocky Flats, Col. Rated at 40 kW, it responds like other vertical-axis machines to winds from any direction.

which other factors may limit penetration. In any case, operating restrictions may have to be placed on large wind turbine clusters (which may lower their annual energy production) in order to achieve the most economical operation of the overall utility system of which the cluster is a part.''

Nothing in the investigation indicated that wind-turbine deployment, of either large or small machines, contains the seeds of irreconcilable future troubles. On the contrary, some of the nation's largest private utilities, including Southern California Edison and Pacific Gas and Electric, are committed to their own examinations of wind energy. Two large wind turbines were built to feed power into the Southern California grid while another is planned soon for Northern California.

The major thrust for both Government and private development programs lies with perfecting wind turbines using the traditional propeller-type blade. But so strong is the mystique of harnessing the wind and so compelling is the inventor's urge that dozens of other innovative designs, ranging from intriguing to absurd, haunt the byways of technology. Hardly a week goes by without some program official hearing from an obscure inventor, an excited hobbyist, or a concerned citizen who just had a brilliant idea.

Predictably, most of the ideas prove to be less than brilliant. Many inventions were ''invented'' years earlier. The hobbyist's idea generates a few



A Darrieus turbine is shown under trial at a California utility. Being airfoils, the blades must turn in one direction for best performance; an unpowered start-up could result in the wrong direction of turning. A friction brake is used for shut-down.

watts, but can't possibly be scaled up. Or the suggestions have fatal engineering flaws. Yet nothing stops the ideas from flowing in, and over the years a number of innovative concepts have received further attention. More than one have proved to be worth serious investigation, either with public or private funding.

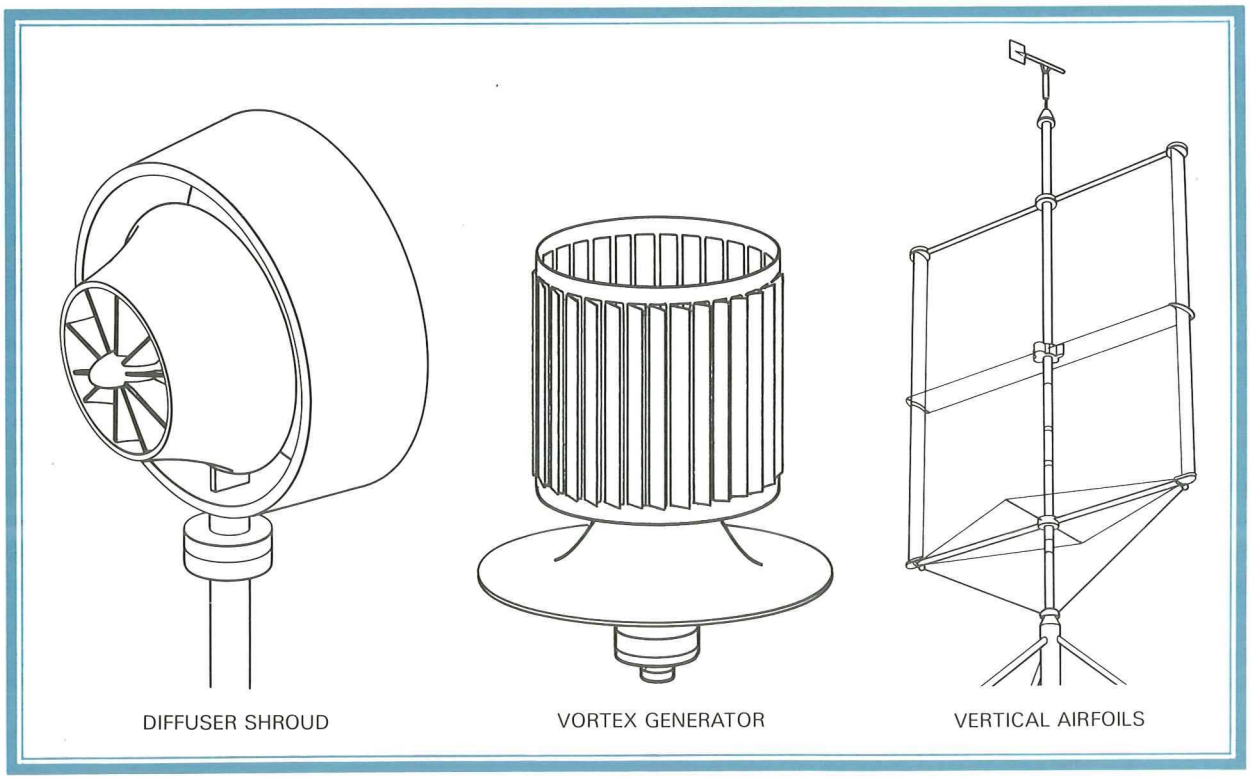
Two innovative systems—the Darrieus rotor and the Cyclogyro or Giromill—have reached an advanced development stage. Both are vertical-axis concepts. Responsibility for research on Darrieus systems, in small and intermediate sizes, rests with Sandia Laboratory at Albuquerque, New Mexico, and its contractor, Alcoa Laboratories. DOE's Test Center at Rocky Flats, Colorado, has responsibility for developing and testing the 40-kilowatt Giromill built by its contractor, McDonnell-Douglas Aircraft Corporation.

Other innovations tend to be small, privately built prototypes. Much lower-level investigation is sponsored by the Solar Energy Research Institute (SERI) in Golden, Colorado. At SERI, Irwin Vas coordinates a variety of wind-related efforts, overseeing some markedly different wind-turbine ideas under a program called Wind Energy Innovative Systems. "It would be a mistake to forget the innovators," Vas said. "The potential is always there for a real breakthrough.

"We're looking at wind turbines that may be quite far away from what is considered normal. There are diffusers, tornado and vortex systems, cyclic pitch-teetered blade designs, and others. Some concepts will be selected for wind tunnel testing, some will just disappear. And then the next step is the proof of concept, building a full-size version."

As Vas said, it's axiomatic in programs such as wind energy, where search can actually precede research, that many proposals or ideas will fall victim to scientific or economic realities. One that has not flowered—the economies of scale simply not being there—was the Madaras Rotor, sometimes called the Train to Nowhere. Julius Madaras conceived the system in the 1920s, hoping to capital-

These unconventional wind turbines have behaved well enough in initial trials to warrant further development. Engineers are aware that in this field a better idea may emerge at any time from fertile-minded original inventors.



ize on the physics of rotating cylinders. Vertically mounted cylinders were set spinning by electric motors. The wind blowing on the turning cylinders generates lift forces. That energy could, in theory, be translated into forward movement to propel a car along a track. The Madaras Rotor would have put a chain of such cars on a circular track. As this Train to Nowhere rolled around and around, alternators geared to its wheels would generate electricity. Restudied in the late 1970s at the University of Dayton, the Madaras concept succumbed to the same cost factors that knelled its demise nearly fifty years earlier.

Another idea that didn't survive the learning curve was called the Bicycle Wheel. Spokes radiating from its center held a large number of airfoils in a circular pattern. The intent was to trap and use the maximum volume of wind. But in tests by Oklahoma State University, its major flaw was apparent: with so much force captured by the many airfoils, the Wheel was vulnerable to damage in brisk winds. Any economy disappeared with the need for super-strength materials.

The same fate could await other innovative concepts. But the stakes are too high to allow for hasty conclusions. "We're willing to take a careful look at ideas," Vas explained, with the air of a man ready and waiting for success. "We intend to make certain that no cost-competitive idea is overlooked."

The procedure virtually guarantees that even the wildest idea will receive some attention, and that each idea gets the attention it is worth. Among innovations being actively pursued at some level by the end of 1980 were several with promise:

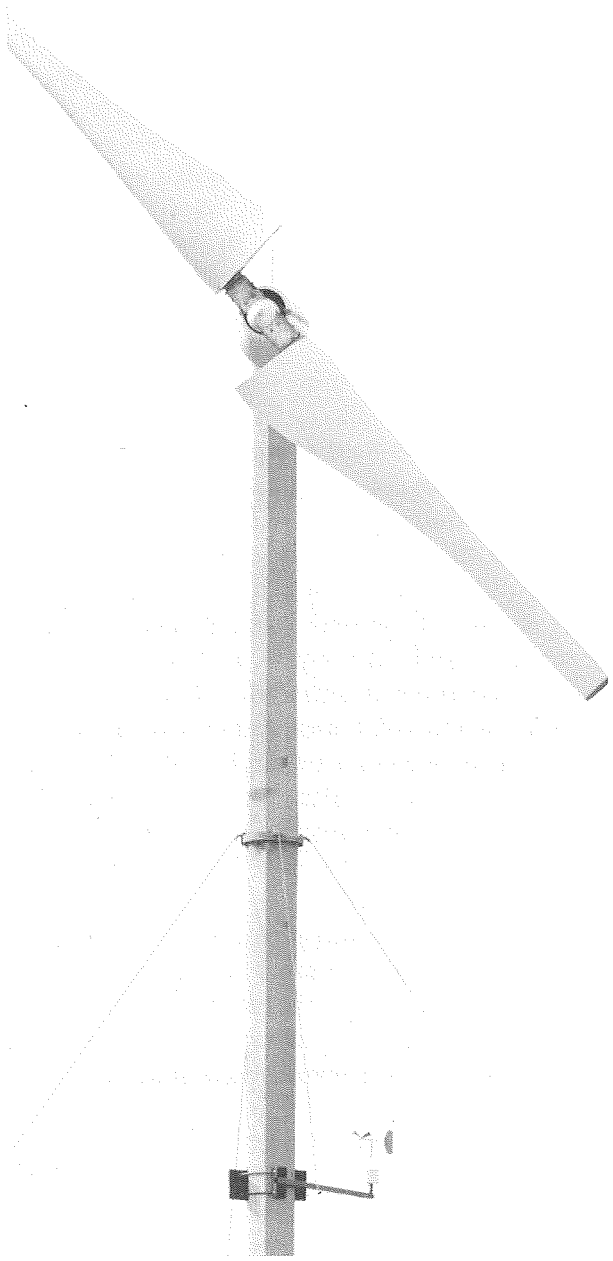
Diffuser systems. Diffusers or diffuser-augmenters resemble the ducted fans familiar on turbojet engines. A diffuser is a tapered or semiconical shroud or duct, small end pointing into the wind, surrounding the blades of a wind turbine. The expanding air flow causes a pressure drop behind the rotor blades, which in turn draws a greater volume of air through the system. Grumman Aerospace Corporation, under contract to SERI, has investigated design combinations for both diffusers and blades, with wind-tunnel tests indicating that significantly increased power may be extracted from a diffused wind stream. "The resulting increased mass airflow (through a diffuser-augmentor) increases the output power and has the potential to reduce the busbar cost. This allows smaller, cheaper turbine blades to be used. . . than for a conventional wind energy conversion system of equal rating."

Tornado-type wind turbines. Another Grumman development, a Tornado-Type Wind Turbine (TTWT) looks like a tall cylinder with an open top, slotted vertical side openings, and controllable guide vanes. Open vanes to windward would let air flow into the cylinder or tower, where it would spiral up and out the top. The spiraling wind quickly creates a vortex, or tornado, with a low-pressure center that draws in additional air through ducts in the tower's base. It is that high-speed air flow that would turn the blades of a vertical-axis rotor mounted inside. Tests with a small-scale model indicate that a TTWT might increase delivered wind power by a large factor.

Circulation controlled airfoils. Promising results of ongoing design and analysis work at West Virginia University have kept this vertical-axis innovation in contention for further development. The concept would use two or more vertically mounted straight airfoils of unique design. The wing-like blades have rounded trailing edges that dump airflow and yield higher lift. SERI funding continues to concentrate on the analytical aspects of turbine configuration, structural and aerodynamic analyses, and system component costs. Meanwhile,

researchers at WVU think that an efficient system can be built that feeds compressed air through tubes to the airfoils. Though some energy would be siphoned off to run air compressors, calculations show significant improvements in overall efficiency for the system.

Unified wind dynamo. With a small prototype developed at Universal Energy Technologies Corporation of Camden, New Jersey, and installed atop a Camden office building, the Unified Wind Dynamo is one of the few innovative concepts to reach the hardware stage with private funding. In reporting to the SERI Second Wind Energy Innovative Systems Conference in late 1980, inventor David D. Deibert claimed his unique design to be simple, efficient, and strong. The turbine itself has eight blades radiating from a small central core and ending at a pair of larger outer rings. The whole system is supported by a central shaft descending from a structure resembling the St. Louis Arch, which allows it to rotate freely to face into the wind. In Deibert's system, induction coils are built into the inner peripheral ring while the fixed outer ring contains permanent magnets. Wind action spins the blades and inner ring, setting up a generating field. Deibert mounted a small model on Camden's Ruetter Building in early 1980. His calculations show a potential output of about 400 watts in a 27-m.p.h. wind. It actually generated some power at wind speeds as low as 3.5 m.p.h. and suffered no damage at winds as high as 54 m.p.h. The design also would benefit by adding a diffuser-augmenter, Deibert reported. Next step, he said, is research "directed into ways to make the unit more economical to produce, handle, and erect."



Rated at 25 kW output, this machine feathers its blades for speed control. With such machines, cost of a suitable tower is not a negligible part of the total installation cost.

Spinning in the reliable breeze, the turbines at Rocky Flats look as if they might cause mutual interference. But this is an artifact of the camera lens; each machine is actually far enough from its neighbors to receive unimpeded winds.

The growing body of wind-energy information provides increasing tools for the industrial managers and the local, State, and Federal officials who face ultimate responsibility for approving or avoiding the exploitation of wind energy. The variables of acceptable wind-turbine sites, the economics of integrating wind-generated power into local utility grids, the tough questions of developing wind-energy systems that both work well and will endure for years, and the optimistic puzzles of examining innovative ideas all have combined to help clarify wind energy's potential.

But the real test of wind energy comes in the field. The work on small turbine systems centered at DOE's Rocky Flats facility and large turbine systems managed by NASA's Lewis Research Center is providing the hard facts upon which important decisions must be made.

3
The Small Machines

The Great American West, nearly two thousand miles from St. Louis to the Pacific Ocean, beckoned settlers in the mid-19th century. It began with a thousand miles of semi-arid prairie. It ended with coastal valleys and hills. Between stood the spine of a continent, jagged mountains that created a torturous barrier. It was a dry and wind-swept frontier eager for moisture, becoming fertile and verdant with rain or irrigation. It was a rich frontier, this American West, to be wooed and won in ways the historians still debate.

Was it a gun that won the West? The Winchester 94 and the leather-slapping Colt revolver have their retrospective supporters. "The Gun That Won The West" is a catch-phrase for cowboy movie fans and Old West history buffs alike.

Or did the wagon trains, the Conestogas and their thousands of plodding farmers and ranchers, win the West? They came in uncounted numbers, by the northern route to Oregon, by the southern route to Utah, Arizona, and California. A century and more later, their wagon tracks give mute evidence across desert and salt flats that hardy folk passed that way.

Perhaps the railroads won the West. With the transcontinental lines completed, the western plains and valleys opened wide to the cheap transport offered by the Great Northern and the three steam-driven Pacifics—the Northern Pacific driving west from Minnesota, crossing the Dakotas, Montana, Idaho, and the Pacific Northwest; the Southern Pacific looping south from the midcontinent to California; and the mighty Union Pacific, linking north and south, carving its trading dominion through the territories and states of the Far West.

Who or what won the West? A plausible answer may be the most prosaic. It lacks the shock of a high-noon gunfight. It can't compare in grandeur

The windmills of yesteryear, like these prairie water pumpers in Nebraska, all but vanished in most parts of the nation as power transmission lines rose in their stead, providing electricity to run the pumps and light the homes and businesses.

Innovative modern wind turbine concepts show some striking differences. These examples at the Wind Systems Test Center in Rocky Flats, Colorado, are (from left): Grumman 8 kW; Storm Master 18; Jay Carter Model 25 with a noise measurement van parked to right of its base; Kaman 40 kW with a crane angled toward top; the vertical oval Alcoa 17-Meter Darrieus; and the vertical three-bladed McDonnell 40 kW Giromill. Wind Systems Building is in left background. Other towers hold wind instruments.

to wagons stretched to the horizon. It has none of the intrigue and power symbolized by long-ago railroad barons.

Did windmills win the West?

No one knows how many wind-driven water pumpers dotted the American landscape in the last half of the 19th century. The number was enormous; as late as 1980, experts estimate that more than 75 000 agricultural windmills continue to pump water into stock ponds, irrigation ditches, and remote, rudimentary kitchens. Certainly the peak of windmill use passed long before, when every farm and ranch relied on the wind for water, when every railroad water tank—and there were thousands of these alone—was kept replenished through wind power, and when uncounted thousands of communities and homes drew their water up from the ground with each twirl of a windmill blade. It gave settlers the water to carve farms and ranches from dryland prairies. It gave railroads the water that became steam in chugging engines. It gave small towns the first trickle of water they needed to grow.

As much as any factor, windmills gave America its chance to settle the West. Now windmills—wind turbines, many of them hardly bigger than the water pumpers of old—are giving a new generation of Americans a new gift drawn from nature. They are generating electricity and making it available in ways only dreamers once dreamed.

There's a breed of engineering innovators—some might call them dreamers, except for the solid substance and the technical success of their work—whose present Mecca is a stretch of scrub prairie between Denver and Boulder, a not quite empty tuck of land in the afternoon shadow of the Rocky Mountain Frontal Range. Here is Rocky Flats, appropriately named, site of the U.S. Department of Energy's Small Wind Systems Test Center. Established in 1976 and occupying one corner of the vast Federal reservation, the wind facility is ideally located. It appears in documents under the designator of WSTC. Officially, it's a test center operated for DOE by Rockwell International Corporation. But to everyone in the wind-energy business, it's simply Rocky Flats.

There in the crest of the mountain wave, winds blow from baby-breath breezes to roaring storms. The wind turbines at Rocky Flats are not the giant generators lighting thousands of lights or powering entire communities. They're the smaller units, in a variety of designs, that produce from 1 or 2 kilowatts at the low end up to 100 kilowatts on the high side. For practical development purposes, the 40-kilowatt units are among the larger ones.

It is easy to say that there is a place in the nation's energy picture for such small units. It is less easy to prove that a healthy market is waiting for efficient and economical products. Rocky Flats has that chore; every experience, every piece of new data, suggests that it is succeeding.

What can smaller wind turbines do? In broad terms, they can produce four varieties of energy:

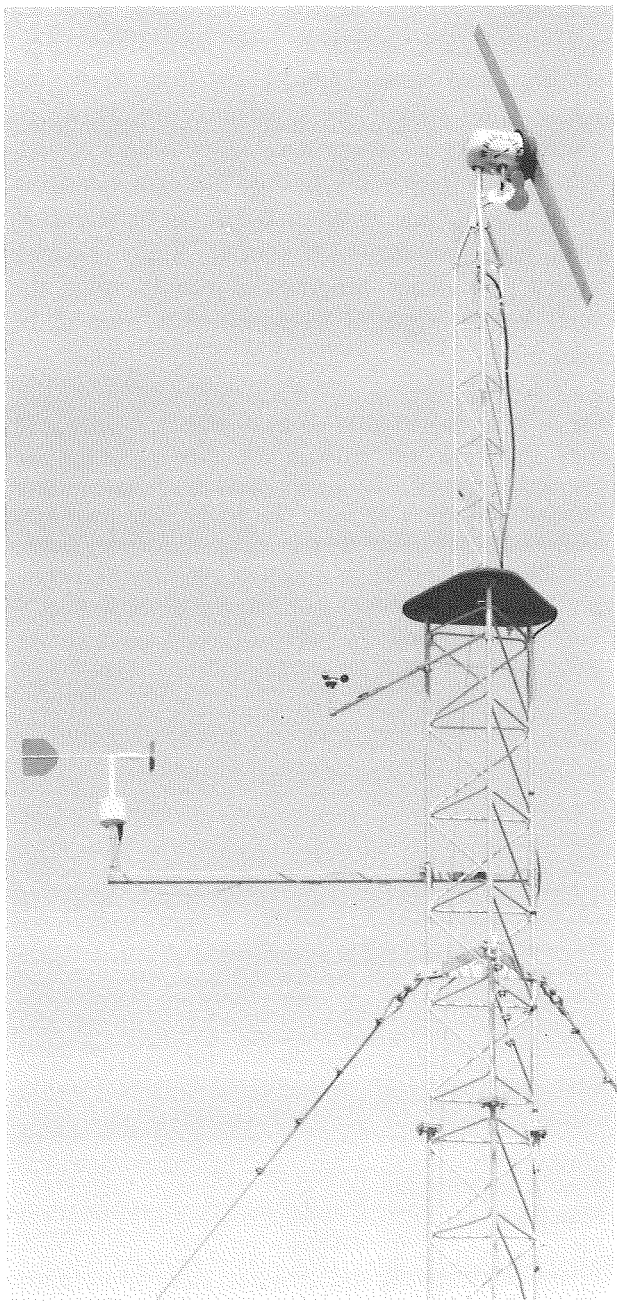
(1) Direct heat, probably warming water to temperatures useful for heating buildings.

(2) Mechanical power, typically pumping water or driving machinery.

(3) Direct-current electricity, storable in batteries and useful in a variety of remote applications.

(4) Alternating current to power the spectrum of modern electrical devices, perhaps interconnected with local utility grids.

In finer terms, wind turbines will come to match specific requirements. Five major development programs are nearly complete. They are aimed at perfecting a 2-kilowatt high-reliability machine for

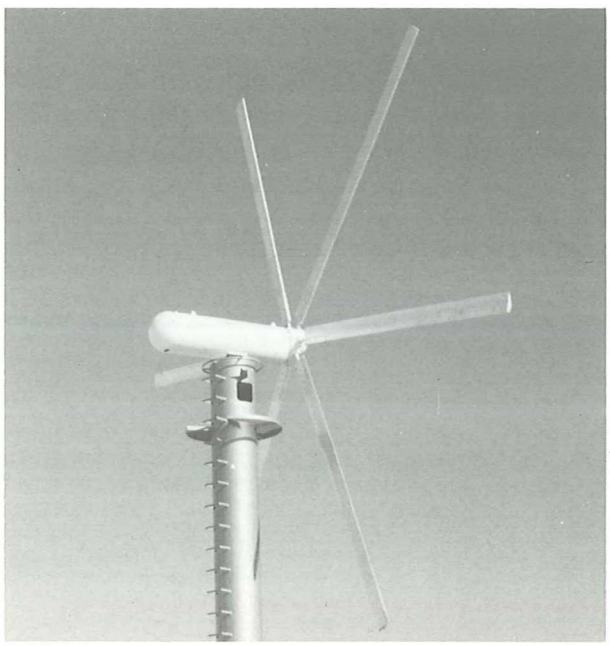


The Whirlwind A240 developed by Whirlwind Power Systems has a design output of 2 kW when the wind speed is at least 25 mph. Overall rotation diameter, tip to tip in this two-blade case, is only 10 feet. This is an upwind rotor in that the wind strikes the blades before passing around the nacelle. The nacelle is oriented into the wind by the fantail device jutting below it.

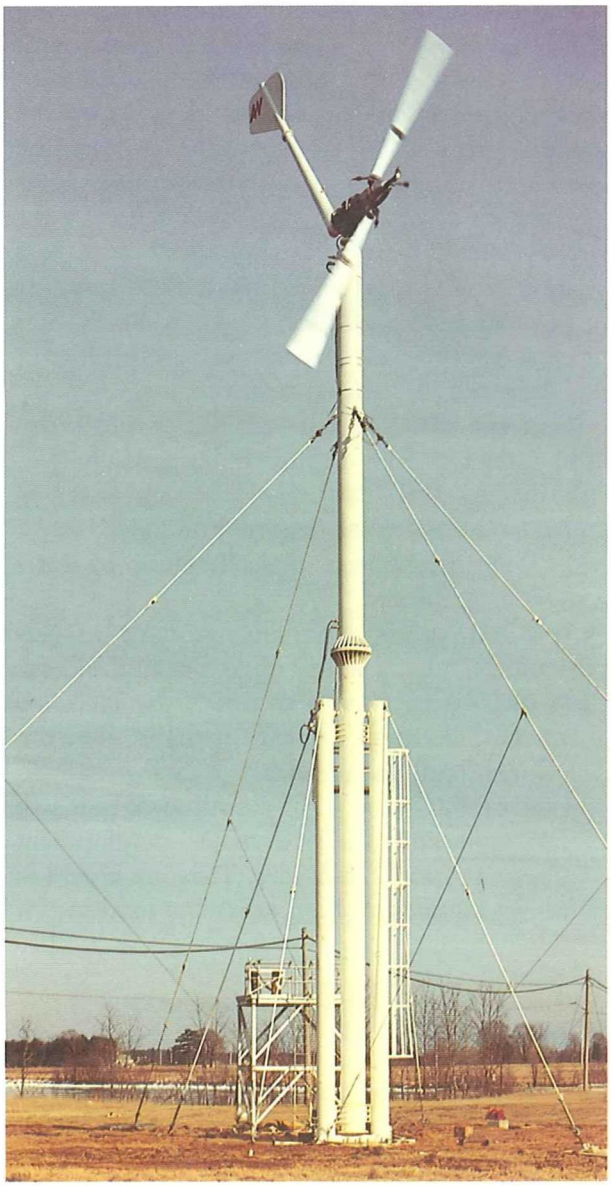
remote uses; 4- and 8-kilowatt wind turbines for residential applications; a 15-kilowatt unit for residential or commercial use, including space heating; and a 40-kilowatt machine with vast potential for agriculture or small communities.

Roger Moment is manager of technology development for Rockwell's Energy Systems Group at Rocky Flats. "Are there problems to be solved in small wind turbines? Of course. We're working toward five major program objectives, plus the usual list of technical questions that have to be considered.

The six blades help identify this Rocky Flats test system as the commercially available Mehrkam 440, a downwind type turbine rated at 40 kW with a wind factor of 25 mph or more. Rotation diameter is 38 feet. The blades have fixed pitch which means they cannot be rotated around their longitudinal axes. The system powers an induction generator. Downwind type means the air travels past the horizontal portion, or nacelle, before striking the blades.



The Aerowatt Model 4100, made in France and marketed in the United States, was the first small wind machine tested under a federal program. Design output was 4.1 kW at 16 mph for this two-blade rotor with a rotation diameter of 33 feet. The testing was done in Ohio.



"Our first and most important goal is to reduce wind-energy costs. If it's not economic, it's not going to have wide acceptance."

Cost goals for small turbines are projected against an assumption of future high production rates—1000 or more units a year. Without large numbers of wind turbines manufactured and installed, unit cost remains too high.

"Yet we're looking at an industry in 1980 where some companies still consider eight or ten machines a year as high volume," Moment said. That leads directly to the remaining four objectives.

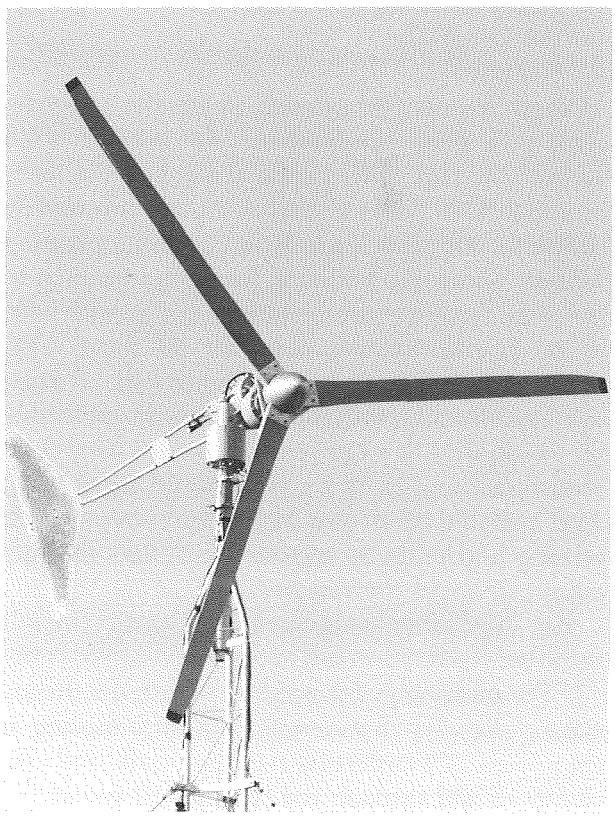
"After cutting costs, we have to improve reliability and safety, promote an industry infrastructure, identify and help eliminate institutional barriers, and increase public awareness," Moment explained. "There is enormous potential for small wind-energy systems, but we need to reach all the objectives."

The list of technical considerations involved in bringing a small wind turbine to maturity is identical in its basics from the work carried on in programs to develop the mid-size and large systems for industrial or utility use. But the thrust of those considerations frequently moves in a different direction. The larger machines almost always will be sited in rural, even remote, areas where they will be optimized for local conditions, be maintained by trained technicians, and have minimum environmental impact.

But the small windmills will appeal to a vastly greater marketplace. They'll be purchased, installed, and maintained by ordinary people, some amateurs and others qualified mechanics. They'll be erected and operated—local codes allowing—in cities and suburbs, in farm yards and fields, at resorts and recreational residences, at remote cabins and distant villages. Someone has already tried to put one atop an urban skyscraper and someone else will convince the neighbors to form a small electrical co-op.

The lure of "free" electricity will attract many, even though the electricity isn't free. If it's cheap, that will be more than enough. The lure of bringing power to remote sites where power previously was unavailable will attract many more. And still more, farmers and manufacturers and

An adjustable tail orients this three-bladed upwind rotor system, the Sencenbaugh Model 1000-14, rated at 1 kW with a 23 mph wind. The rotor rotation diameter is 12 feet. The system is designed for use in charging batteries, principally wet cell, automotive type batteries.



businessmen, all eager to cut the cost of power, or at least to stem its inexorable increases, will become owners and operators of small wind-turbine systems. The numbers could easily reach into the hundreds of thousands.

It is those ordinary people who must be considered when such systems are planned.

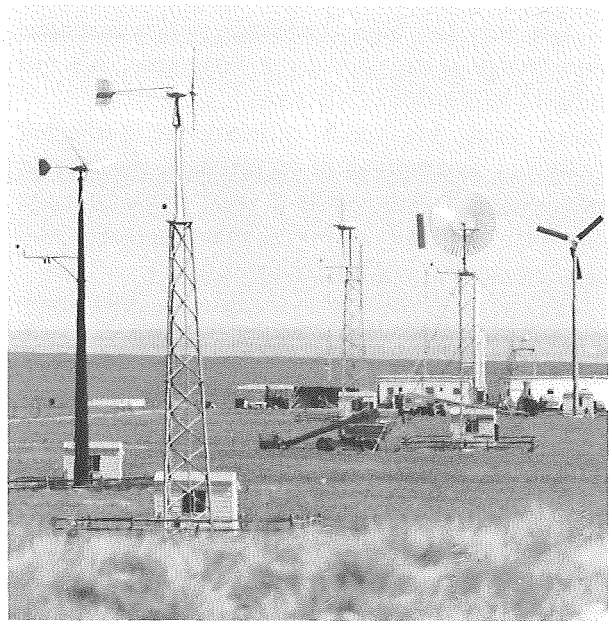
In each of seven key categories, there must be an optimum convergence of low cost, technical effectiveness and longevity, and acceptability by an average consumer. The categories:

Vibration
Efficiency
Noise
Performance
Output format
Serviceability
Safety

Roger Moment compared the challenge to designing a good automobile. An average wind turbine, he said, will operate about half the time, or about 4400 hours a year. A typical automobile driven 15 000 miles a year is, in contrast, operating for only about 500 hours. If the wind turbine is to be useful, it must operate automatically, with little or no human intervention, for all those 4400 hours. It must start and stop automatically. It must operate virtually without breakdown, preferably for twenty-five or more years. It should need little service; an hour or two a year should be enough. And it should do all that with minimum noise, no adverse impact on its surroundings, and absolute safety, whatever the weather.

An impossible assignment? Moment doesn't think so.

"The technology for good wind systems already exists," he said confidently. "What's missing is the process of transferring it economically and efficiently to and through the commercial system."



August 1978 photo shows some of the first generation modern wind systems given tryouts at the Rocky Flats test site. From left are: 6 kW Electro; Northwest Eagle 3 (3 kW at 27 mph); Zepher Wind Dynamo (15 kW at 31.3 mph); American Wind Turbine AWP-16 (2 kW at 20 mph); and Grumman Windstream 25 (15 kW at 26 mph), the only one of the five that did not reach the marketplace at one time or another.

The experts at Rocky Flats, with five years of experience in designing, developing, testing, and evaluating a variety of commercial and prototype machines, are convinced that no breakthroughs are needed to make small wind systems a significant element in the U.S. energy budget. It's a matter of using technological skills that already exist, picking and choosing from a catalog of concepts to put together the best system.

The pieces are there. It's the finished puzzle that's being sought.

But Moment counsels patience and understanding. "If people expect too much, they'll be

disappointed,'' he cautioned. ''We're still learning.''

That learning process applies both to developers and users. Among the early lessons learned at Rocky Flats was a wariness of manufacturer's claims. The most common disappointment comes when a wind turbine fails to deliver the power its owner expects. 'Rated output' can be deceiving, Moment said, because it is a number based in part on ideal wind speed. A turbine with a rated output of 2 kilowatts at 24-m.p.h. wind speed is doing well to produce those 2 kilowatts 10 percent of the time. ''The effective power output of a turbine probably will be less than the optimum in published specifications,'' Moment pointed out.

The major technical problems concern vibration and efficiency. Too many existing wind turbines are subject to vibration stresses, largely because they are built from off-the-shelf components. There are few parts of any small wind-turbine system designed specifically for their job. Blades, of course, are generally custom-designed and manufactured. But support towers, gearboxes, generators, electronic components, and almost everything else that goes into a small wind system may have been originally designed for another purpose. Too often, the result is an engineering mismatch that leads to mechanical vibrations that can cause fatigue failures. Perhaps the vibrations will not be ultimately destructive, or even dangerous. Perhaps. But careful attention during the design and development process, including use of parts specifically designed for wind turbines, can eliminate the problem entirely.

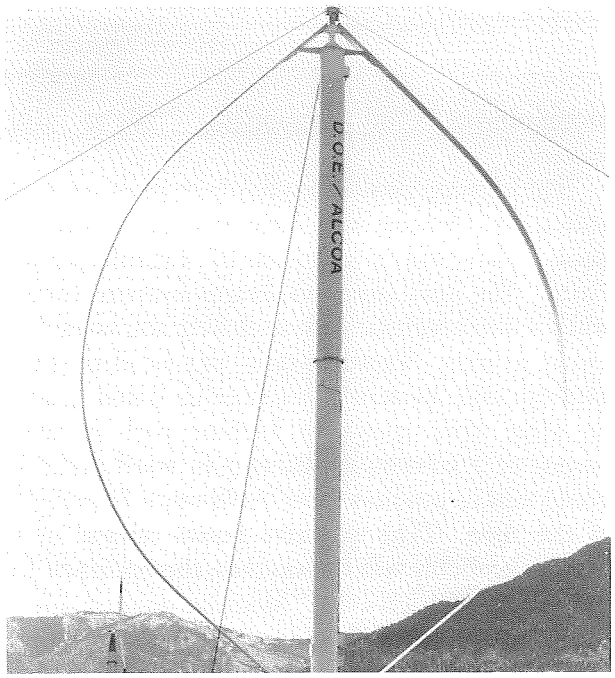
The Enertech 2 kW High Reliability prototype has a design output of 2.1 kW at 20 mph from its two-bladed downwind rotor. The unit is designed for battery charging in remote locations. Rotation diameter is 16.4 feet.

Efficiency is a tougher consideration. With the theoretical maximum wind-turbine efficiency well-established at 59 percent, most small systems previously operated in the 20-30 percent regime. Yet significant improvement in power generated at particular wind speeds can be a heavy driver in reducing overall system cost. Blade design, gear ratios, size and type of generators, even tower height and style all can be optimized to improve efficiency.

Noise turns out to be little problem with small wind turbines. Typical decibel levels fall between the noise of an average living room and an average office—hardly enough to cause concern. And even a few dozen yards from a turbine, particularly upwind, there is likely to be no noticeable noise at all.

Similarly, local conditions are a crucial factor in power production and must be included in any analysis of wind-turbine usefulness. Identical turbines will seldom generate identical power in different locations. But Rocky Flats testing has shown that modifications as simple as changing gearboxes may improve performance and allow better match with local winds. More important, turbine users should do an initial analysis that takes local conditions and machine performance into account, and then select the optimum turbine system.

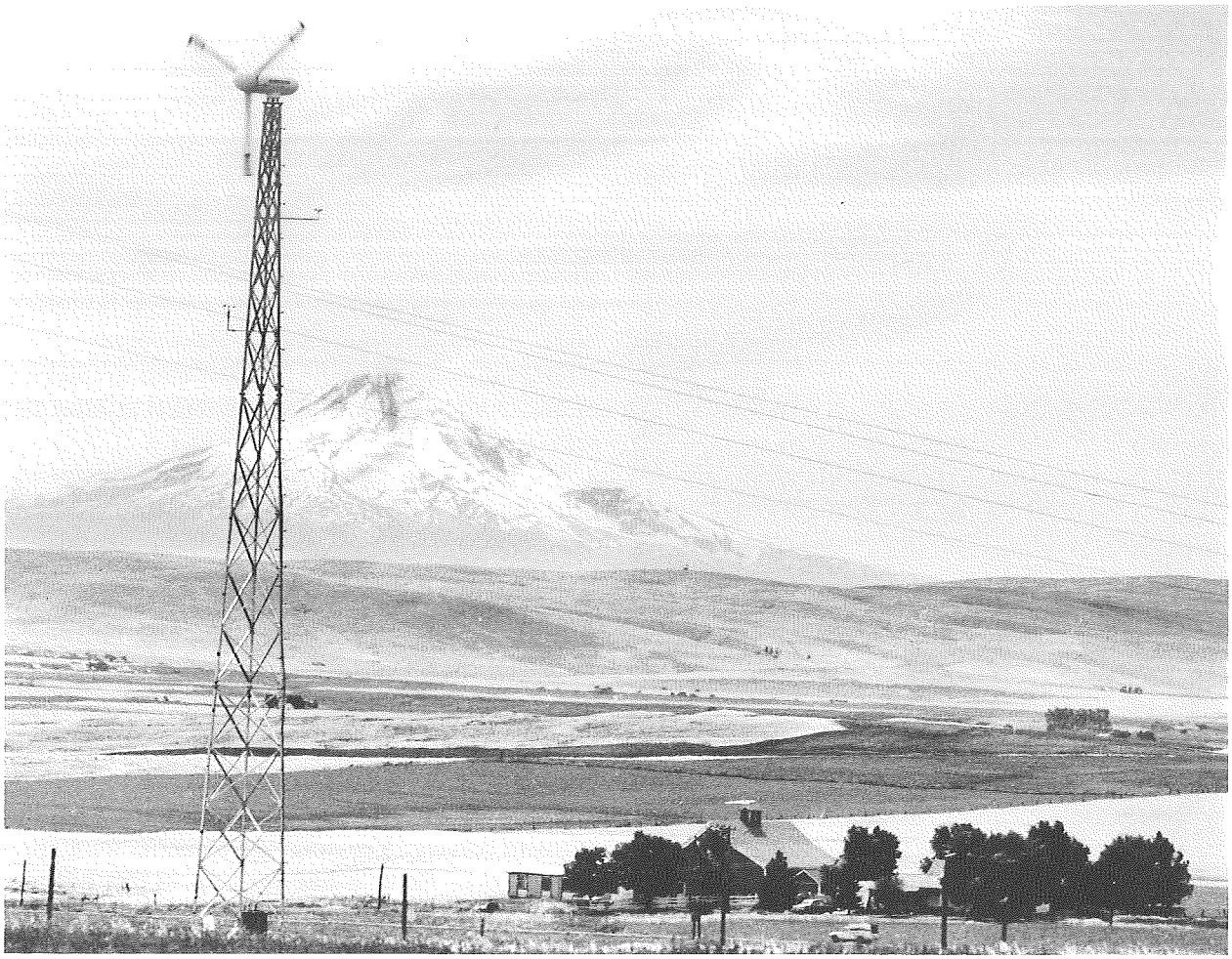
Output format is one of those considerations that is an important issue early in a project, then sets all manner of requirements as the project matures. Imagine the variety of specifications between a wind turbine intended to generate direct current at a remote site, another to produce enough alternating current for a single-family residence, and still another feeding excess capacity back into a utility grid. The latter potential particularly concerns the utilities themselves. Mismatched power, a machine out of synchronization with the local grid, can disrupt distribution



Overall height of this prototype is 94 feet. Rotation diameter is 56 feet. This is the Alcoa 17-Meter Darrieus developed under a project managed by Sandia Labs. The vertical axis rotor powers an induction generator. Design output is 100 kW at 31 mph. The two blades are fixed pitch type.

to wide areas. Of equal concern, sudden changes in wind strength can cause either power surges into the grid, or rapid power demand from the grid. That means standby generating facilities are mandatory. Such questions must be examined with great care during design and development of small wind systems and solutions found that protect utilities, their customers, and wind-turbine users. "In addition to all that, it will take a large number of wind turbines in place before utilities can think about depending on them," Roger Moment said. "Until then, utilities must maintain that expensive reserve capacity."

Turbine servicing must be reduced to a minimum. The few maintenance items include annual lubrication, checking or replacing fuses, replacing



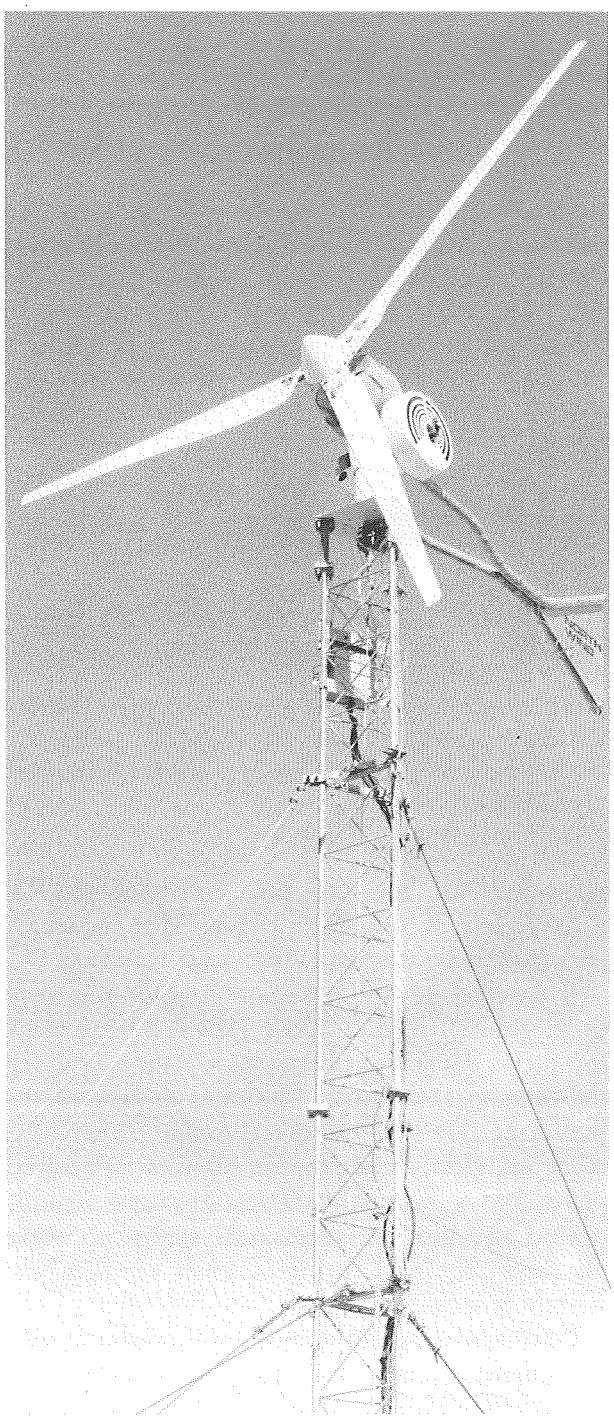
This three-bladed downwind rotor with tip-brakes is the Enertech 1800 installed on a farm near Goldendale, Washington. The commercially available machine is designed to produce 2 kW at 24 mph in utility-interconnected applications. The tip-brakes serve to slow rotation only when wind conditions become excessive.

burnt slip-ring brushes in the generator, rarely replacing a failed diode or other electronic component, and a fresh paint job now and then to prevent corrosion.

Safety is a real concern. Scores of small wind turbines have been tested at Rocky Flats under conditions from benign to severe. Most survived. But now and then, the unexpected has occurred. Towers have buckled and collapsed, sometimes because of high winds, sometimes because long periods of vibration took their toll. Blades have suddenly come loose, flying from their high perch on dangerous trajectories. And entire turbines have fallen from tower-tops, crashing to the ground. There is no record of serious injury from such events, which are rare. But in the early 1980s, wind turbines, too, are rare. The safety goal at Rocky Flats is to make certain that accidents remain rare even when turbines are common.

If progress in the DOE-sponsored development programs managed at Rocky Flats is a measure of the future, small wind systems are moving along the road to abundance. Machines in each of the five sizes matured rapidly through early 1981. None was clearly ready for the commercial marketplace, but a dozen machines advanced steadily toward the goal of operational status. In these machines, the near future of small wind-turbine systems is seen.

"An increasing number of applications for very small wind systems involve rural and remote needs for powering repeater stations, seismic monitoring



stations, and offshore navigational aids, as well as for pumping water into remote stock watering tanks," said a recent Rocky Flats report. "An economical, rugged wind turbine with an output of 1 to 2 kilowatts has been identified as ideal for such applications."

Three such machines are under development—a three-bladed turbine with blades facing into the wind (upwind), a two-bladed turbine with blades facing away from the wind (downwind), and a three-bladed cycloturbine. Each machine should produce at least a kilowatt when the wind reaches 20 m.p.h. and have a basic cost of no more than $1500 per kilowatt in 1977 dollars. But there's more going into these sturdy little machines than that. The specified service requirements for one machine would seem to require a science-fiction robot to survive. Yet since the machine went into test at Rocky Flats, it has lived up to this billing, under the limitations of weather at the test site:

- Power output of 2 kilowatts direct current minimum in a 20 m.p.h. wind.
- Operation at temperatures between – 20 and 140 deg. F.
- Perform equally well in torrential downpour, sand or dust storms, heavy ocean spray.
- Be generally unaffected by ice buildup to 2.5 inches thick, by impact of hail stones up to 1.5 inches, or by heavy industrial smog with salt fog and spray.
- Survive 120-m.p.h. steady wind with gusts to 165 m.p.h., and repeated lightning strikes during thunderstorms.

The North Wind 2 kW High Reliability prototype can rotate its blades into a horizontal position like a helicopter in order to control the power output, for shutdown, and to protect the system in high winds. The large spring on the side is part of the pitch-up control system. Design output is 2 kW at 20 mph with a diameter of 16.4 feet. This is an upwind rotor.

• Operation in a remote location for twenty-five years, with just one maintenance day per year and at least ten years mean time between failures.

A lot to expect? Certainly. But that's what it will take to create a machine to do the job required. Early results are a high tribute to the ongoing vitality of American ingenuity. With more than a year of testing complete, the machine is living up to its billing. Machines developed by other companies have similarly made significant progress toward meeting the requirements for high-reliability machines.

But there's work to be done. System economy is penalized by the cost of the tower—which can exceed 40 percent of total expense. Initial testing of early prototypes also revealed the kind of improvements that could shave the annual cost of energy for these systems. For instance, one firm has replaced its wooden rotor blades with fiberglass blades and its original gearbox with a less expensive unit. Another company similarly went to fiberglass blades and increased its energy output through improving the blade airfoil and other modifications recommended after Rocky Flats did

Row 1 at Rocky Flats has a group of prototypes. From right foreground to left are: Enertech 2 kW; ASI/Pinson 1 kW Cycloturbine; North Wind 2 kW in its shutdown mode; and, in background below the vertical blade of the Cycloturbine, the three-bladed Bergey Wind Power BWE 1000 rated at 1 kW at 25 mph. In lower left is the three-bladed Kedco 1620 downwind rotor rated at 3 kW at 25 mph. It has a diameter of 16 feet.

its initial round of testing. And in a recent evaluation of developmental systems, Rocky Flats pointed out that its own requirements drove costs upward. "Tower costs could be halved if wind speed requirements were relaxed for less severe environments," researchers reported.

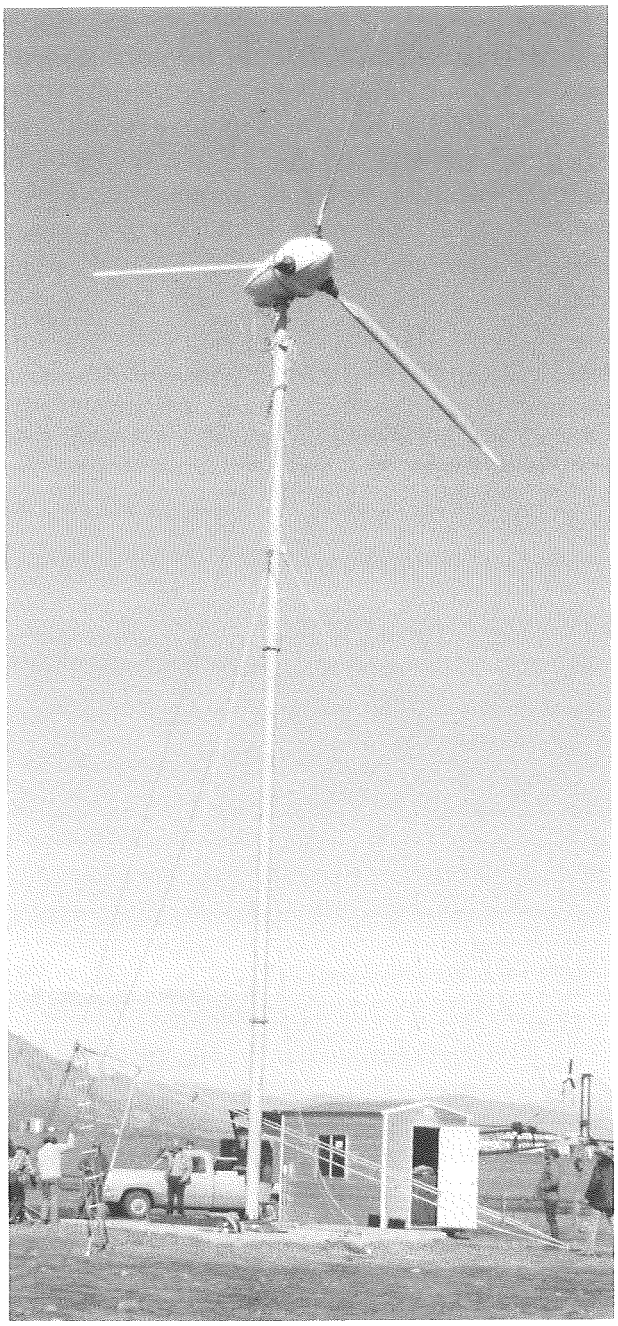
The slightly larger wind machines under development are likely to enjoy broad acceptance later in the 1980s. "The peak demand for an average home without electrical heating is approximately 8 kilowatts," according to a 1980 Rocky Flats report. "A wind system of this size would have wide application to powering homes or farm buildings. The goal of this program is to design and build a prototype 8-kilowatt wind system at an initial cost to the user of $750 per kilowatt (1977 dollars), excluding secondary components."

Design goals for the systems were moderately stringent, but aimed at economy.

- 8 kilowatts minimum out at standard 60 hertz, 120/140 volts alternating current.
- Fully compatible with either electrical utilities or internal-combustion backup generators.
- Rated for 20-m.p.h. winds, with survival in a 165-m.p.h. wind.
- Twenty-five year minimum lifetime.

Three contractors took on the task in 1977 and their prototypes were under test in 1980. All designed downwind machines. One produced an 8-kilowatt turbine, while the second developed an 8.5-kilowatt system. Both had relatively high costs with tower and electrical controls amounting to nearly half of the cost of one entry and the power conversion subsystem running at 30 percent of the project cost for the other. Estimated cost-of-energy thus was 7.8 cents per kilowatt-hour for one and 7.5 cents for the other. The third entry was a three-bladed machine rated at 11 kilowatts. By increasing rated output and concentrating on an efficient rotor and hub, this entry was able to produce power for about an estimated 5.8 cents per kilowatt-hour.

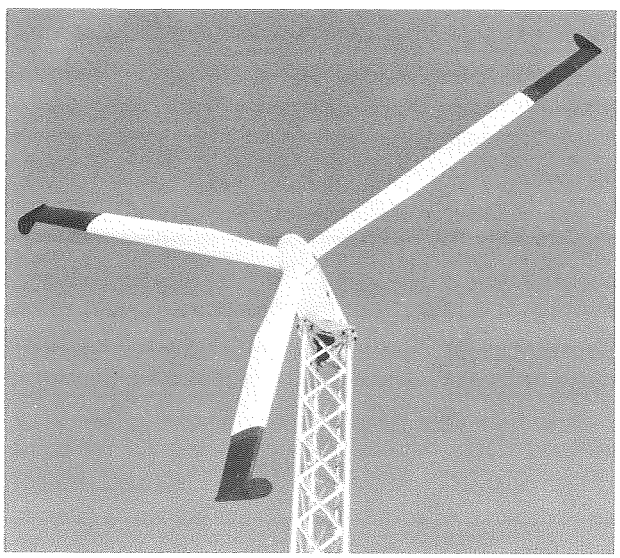
Installation of the first machine at Rocky Flats, the Windworks 8 kW. Diameter of the downwind three-blade rotor is 33 feet. The design output was 8 kW at 20 mph. The wind turbine featured a hydraulic control system and a samarium-cobalt magnet, direct-drive alternator connected to utility lines.



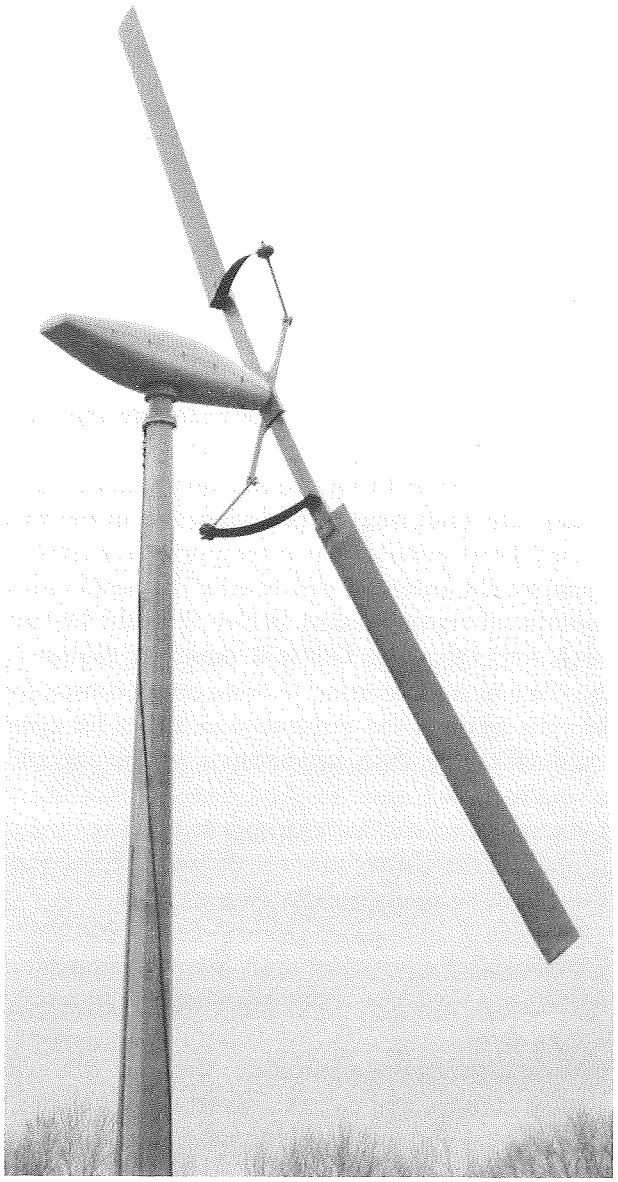
Field testing at Rocky Flats revealed that all three systems could yet be improved, particularly with the use of lighter materials. The estimated economy of the three-bladed machine improved to about 4.7 cents per kilowatt-hour, with the recommended Rocky Flats modifications.

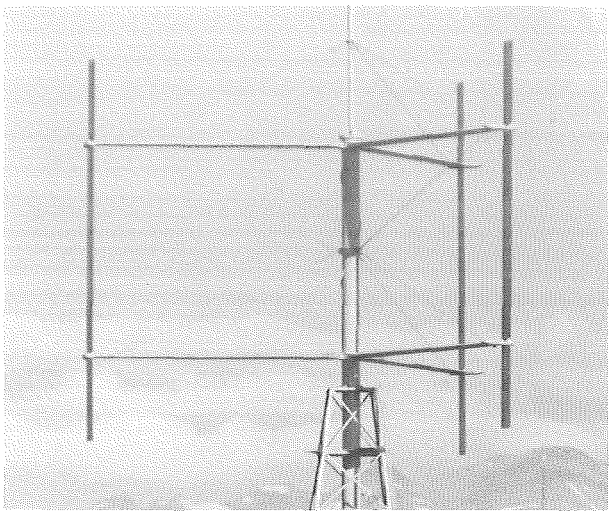
Only two machines entered the 15-kilowatt development round. One scaled up its 8-kilowatt unit, getting what Rocky Flats evaluators called "significant improvement." The other began designing a turbine based on one of its commercially available machines. In both cases, the 15-kilowatt turbines remained in early development during 1980, with testing at Rocky Flats remaining in the future. Design requirements for these machines were similar to 8-kilowatt turbines, except for a reduced survival wind speed of 125 m.p.h. and an energy cost goal of 3 cents per kilowatt-hour for the 10 000th production unit.

The Enertech 15 kW is designed to produce 51 500 kWh per year with an average 12-mph wind. Design output of the downwind rotor is 15 kW at 20 mph. Diameter is 44 feet. The turbine system's one-phase induction generator is designed for direct connection with utility power lines through a user-operated control box. Tip blades are installed to help avert damage in excessive winds.



Graphite-epoxy flexbeams and pendulums on the inboard portion of each blade serve as the bearingless rotor control system for the UTRC 15 kW prototype that has a maximum output of 21 kW at 20 mph. The pendulums twist the beams and, in turn, the blades as the rotor rpm increases. When the blade pitch angles lessen their aerodynamic lift decreases, limiting the rpm to the desired level. This downwind rotor has a diameter of 44 feet.





This vertical axis prototype is the McDonnell Giromill with a design output of 42 kW at 20 mph. The three parallel blades are 42 feet long. The diameter of their rotation circle is 58 feet. The electronic control system includes wind sensors and allows self-starting, pitch setting for maximized output throughout the operating range and automatic shutdown in winds greater than 40 mph.

With the 2- , 8- , and 15-kilowatt machines in various stages of development or improvement, the larger 40-kilowatt turbines went into test at Rocky Flats in 1980—and immediately ran into trouble. The 126-foot-tall Giromill collapsed in a wind storm while being checked on a maintenance stand. The fault was not in design, but in the way it had been installed on a temporary test stand. Even so, the machine was heavily damaged, with months of repair needed before it could be put back into test. The Giromill does not require a nacelle and is self-starting. A wind sensor constantly sets the pitch of the three vertical blades for optimum efficiency. Also, important to system cost and to maintenance, most of the Giromill's machinery is located at ground level for easy access. The design thus eliminates heavy tower structures that increase the cost of so many turbine systems.

The other 40-kilowatt developmental machine, a two-bladed downwind unit, showed promising results—and the customary potential for improvement. Rocky Flats recommended, among other modifications, wood composite blades, a teetered hub, and simplified electrical controls. With those changes, the turbine should theoretically approach its goal of 3 cents per kilowatt hour.

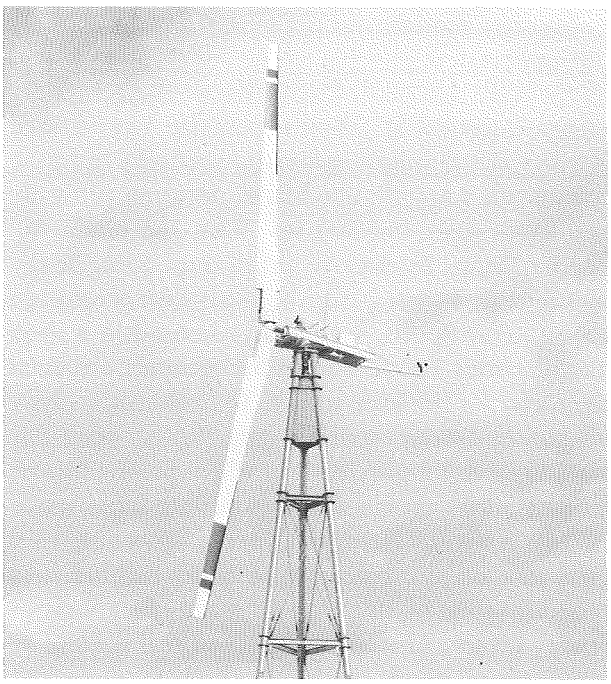
Roger Moment is enthusiastic about these small turbine systems, particularly the 40-kilowatt versions. "There is a future for all the sizes to be marketed in different quantities," he said in early 1981. "The 40-kilowatt machines alone have agricultural applications, pumping water, or running small dairies. The machines will be used in villages and mining camps, for communications systems, on offshore oil rigs, in national parks, and for any number of rural or other private applications.

"I don't see much urban application yet, though. With small lots, tall trees and taller buildings, cities aren't ready for wind power. Someday there may be a good urban system, but we're not there yet.

"Even so, the future isn't limited by technology. It's a matter of economics and acceptance, and I think we're almost there."

The full span of testing at Rocky Flats falls into five distinct categories. In addition to testing the developmental prototypes, Rocky Flats also tests commercially available machines, commercial prototypes, special machines aimed at trying new concepts, and machines destined for field testing in various parts of the nation. The purpose of the program is to provide proving-ground service to a small industry that will accelerate wind-turbine commercialization. Data are supplied to manufacturers in monthly reports, complete with recommendations for modifications or improvements.

"We also make sure that machines actually deliver according to specifications," said Test Manager John Balcerak. The program includes dynamometer runs with measured inputs, vibration tests, even controlled velocity tests on a railroad flatcar. Finally, the turbines are installed at one of thirty test pads at Rocky Flats and run for about a year. "In that time, we'll get wind storms, ice, dust, and almost every good and bad condi-



Intended for agricultural and industrial use, this Kaman 40 kW prototype is designed to generate 134 000 kWh per year at a 12-mph average wind site. The downwind, 64-foot diameter rotor drives an induction generator with a design output of 40 kW at 20 mph.

tion to see just how reliable these machines are,'' Balcerak pointed out. ''Reliability is the key to success. If you have a 5-kilowatt machine running 90 percent of the time, you're better off than with a 10-kilowatt machine that's down much of the time for maintenance or repair.''

After more than five years of testing small wind turbines, the Rocky Flats organization is confident that the machines are getting better. As Balcerak sees it, easy maintenance is a key to long-term survivability and commercial acceptance. ''If you can keep it running, it'll pay off!'' he said. The reliability of small turbines has improved each year as manufacturers take the data from Rocky Flats tests and feed it back into their own programs.

''There's an increasing amount of corporate research funds being spent, too,'' Balcerak said. ''Right now, we're an aid to an industry that just doesn't have the manpower or the resources to have everything itself. This work has to be done; it's important.

''But as the industry grows, the test center will have to become self-supporting. We're getting more and more requests to help this industry develop.''

The potential for a successful industry grows increasingly as small wind turbines steadily improve. The machines are no longer for hobbyists, hermits, and handyfolk. They're becoming an element in the energy picture available—and desirable—to vast segments of America. Rocky Flats has developed a step-by-step process for examining your wind-turbine potential. The steps are:

1. Evaluate potential legal and environmental problems.
2. Evaluate your energy requirements.
3. Evaluate the wind resource at your proposed location.
4. Evaluate the application.
5. Select system and components.
6. Evaluate the cost of the system, considering Federal and State incentives.
7. Re-evaluate energy requirements and legal/environmental impacts, if necessary.
8. Evaluate alternatives in buying, installing, and maintaining a wind system.

Those steps are likely to be taken by thousands of Americans later in this decade. Given the galloping progress by the machines that helped win the West, they are steps certain to be taken with hope and realistic expectation.

4
The Big Turbines

Among the first of the experimental wind turbines to produce utility-useful power was the one above at Culebra, Puerto Rico, and a sister machine at Oahu, Hawaii, on the facing page. Both are 200 kW turbines that start delivering power in 10 mph winds, and rated power at about 22 mph.

Another sunrise, and the westerlies barely shiver the dewy air in the bay at Culebra. The calm is unusual on this small Puerto Rican island halfway eastward toward St. Thomas and the Virgins, and it won't last. Sunlight glows momentarily from the red tip of a propellerlike blade, pointing vertically and more than 160 feet up. Soon the blade will begin to turn, its massive airfoil responding as the breeze reaches just 7 m.p.h. With each revolution above cut-in speed, a generator housed in a sleek nacelle, itself 100 feet from the ground, produces electricity for the local utility. With that first input of power, today coming post-dawn, yesterday coming at midnight, each new day begins for the United States program in developing large wind-energy systems. Here at Culebra, the Sun rises each day on the easternmost wind turbine in a program that is helping to shape the nation's energy future. That same Sun soon will illuminate other giant wind machines sited to span the breadth of the North American continent.

After Culebra, the Sun rises on a similar turbine far to the north at Block Island, Rhode Island. The dawn line sweeps west, bringing another day to an even larger turbine at Boone, North Carolina, and then to the grandfather program site at Sandusky, Ohio. It takes two more hours for first light to strike the turbine at Clayton, New Mexico, and Medicine Bow, Wyoming, and another hour yet for dawn to come to the three awesome towers at the nation's first wind farm just north of the Columbia Gorge at Goodnoe Hills, Washington.

Finally the last of the experimental machines, on the north shore of Oahu, Hawaii, feels the touch of daylight. Dawn in Hawaii is early afternoon in Culebra, mid-morning in New Mexico. From the Caribbean to the Pacific, these are no backyard windmills. Nor are they hastily planned units meant to generate more publicity than

power. These machines are giants, synchronized with local electrical utilities and producing hundreds or thousands of kilowatts of energy. The smallest of them can supply fifty homes when the winds are right. The largest are the forerunners of machines that may find wide acceptance as major generating units for the largest utilities.

It's the early 1980s and another long day of wind-turbine activity is underway. For some sites, it will be a day of steady power generation, converting the energy of wind into the usable energy of electricity. For other sites, it may be a day of partial or total calm, or a day of down-time for maintenance or modification. In the manner of all developmental programs, there is no such thing as perfection. But in the manner of programs where success promises, each day brings new data, new insight, new optimism that the technology is proving itself.

It will be a day of more than eighteen hours, from sunrise in Culebra to sunset in Oahu. In that long day, the big turbines being developed to help feed America's appetite for electricity will move a step closer to operational status. The lessons learned since the program began in 1973 are paying off. For the Federally sponsored wind-energy program, ultimate success means phasing out the Federal Government's involvement as private industry takes over.

The seeds that grew into the world's largest effort aimed at harvesting the wind were sown by the Organization of Petroleum Exporting Countries (OPEC) in their 1973 oil embargo. The crisis precipitated by that embargo led to a national reexamination of energy. Reaction was rapid. In little more than a moment in history, the United States extended technological feelers in scores of directions. Concepts, ideas, proposals were examined; some seemed feasible, but most were rejected. Among the technological avenues given a green light was wind-turbine development. Already being considered by the National Science Foundation, a broad-based program was authorized under NSF's Research Applied to National Needs (RANN) program.

Evolving through the mid-1970s, the wind-energy program was turned over to the Energy Research and Development Administration (ERDA), then to the newly formed Department of Energy. But while administration of the overall program changed, responsibility for the major hardware effort in developing the largest wind turbines remained with the National Aeronautics and Space Administration. It was NASA's aeronautical experience that paid off in developing giant airfoil blades, its hardware development experience that paid off in integrating a total system, and its unique management experience that brought together a complexity of elements to yield maximum benefit.

Prime NASA responsibility for the large wind-turbine program was assigned to the Lewis Research Center in Cleveland. Here NASA engineers had done pioneering research for high-speed turbine engines for advanced jet aircraft, designed and built spacecraft and space-borne instruments, performed thousands of wind-tunnel tests on turbine blades and air foils, and had the major agency expertise in rotating systems. The personnel nucleus with wind experience was there, too. Ron Thomas and Joe Savino already were wind-energy theorists. Thomas became program manager for large wind-turbine development. Savino made major contributions, including tracing the development of wind machines, both modern and ancient, and putting current development needs into perspective.

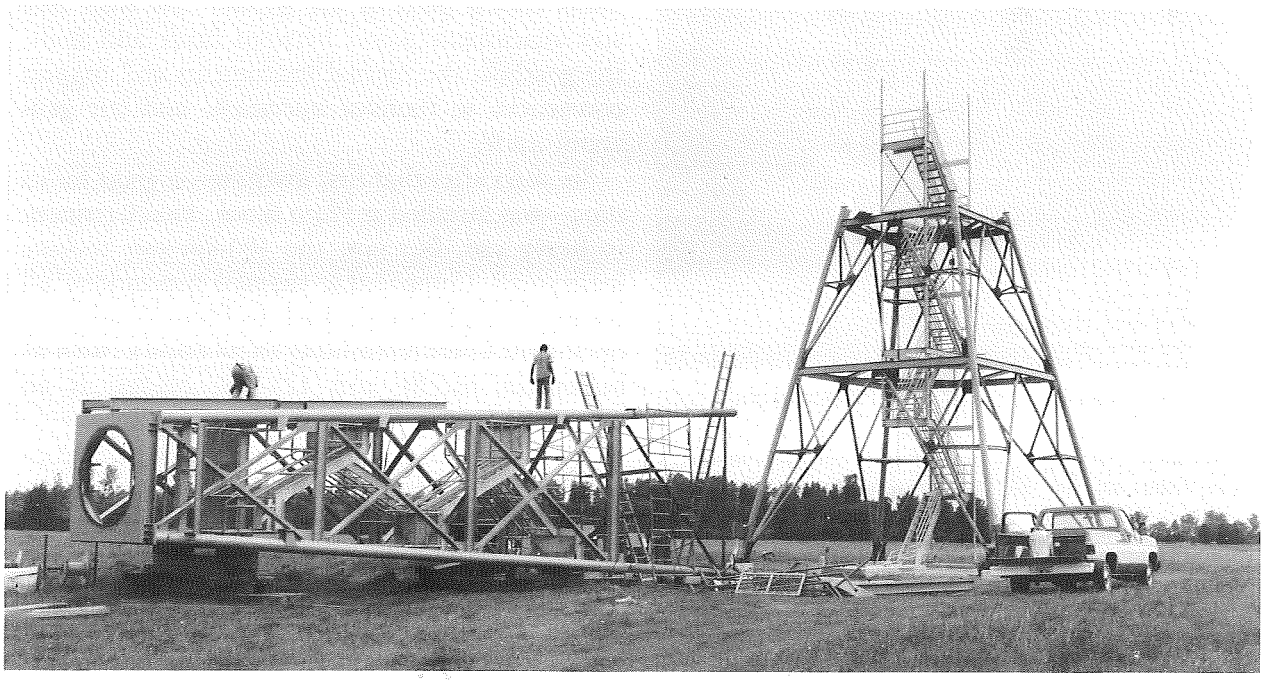
Assistant Program Manager Darrell Baldwin recalled the early days, when most of the learning about large turbine systems remained ahead. The

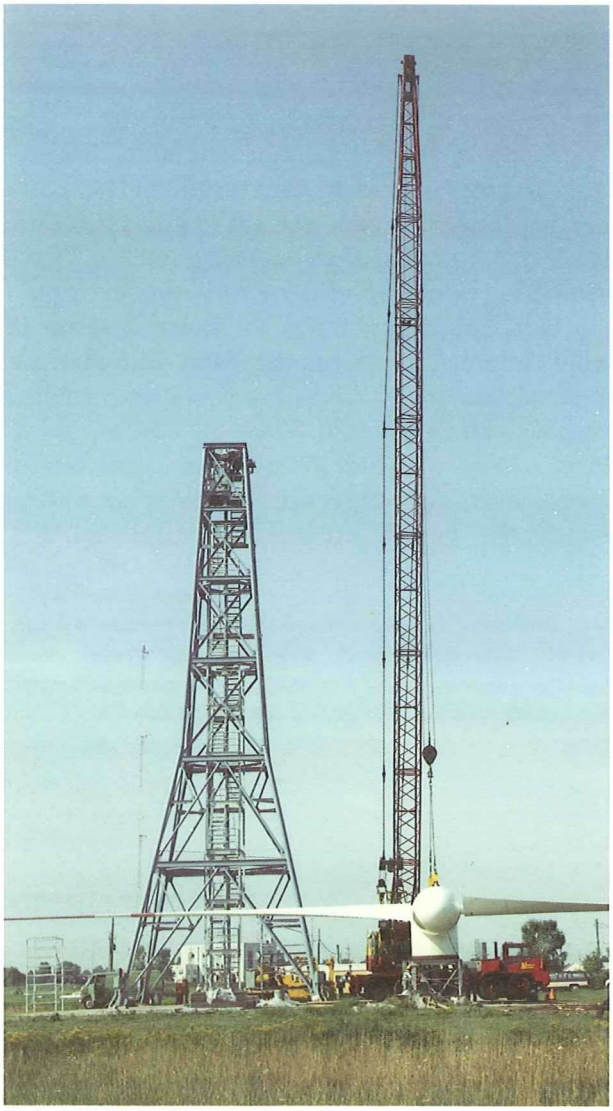
generators themselves seemed to offer little worry. Commercial generators had been around for nearly one hundred years, the end product of a mature technology. The industry norm is to build generators that will run for thirty or forty years, or more. It was the rest of the system, the blades that make the generator's shaft turn, the tower that supports the whole unit, and the necessary peripheral equipment that needed work. The energy source would not be something well-understood, such as controlled high-pressure steam from coal or oil-fired boilers, or carefully channeled water cascading through a dam. And there were new system questions, including vibration, structural dynamics, fatigue, and control methods.

"The historical reviews showed us very clearly that every large windmill system had been plagued by mechanical problems," Baldwin said. "The standard joke was that we were developing fatigue-test machines instead of wind turbines. The key to beating fatigue breakdowns was to understand the loads and dynamics of an operating system. That's something nobody had done with any precision.

"Our first thought was to design a series of wind-tunnel tests to get the data. But then we realized that we are dealing with an uncontrolled variable—the wind itself. There are dynamic problems related to wind shifts, gusts, variations in speed, even air turbulence. There is no way to handle that kind of situation in a wind tunnel."

The beginning of the beginning: steelwork for the pioneering Mod 0 machine being built up in 1975 at Plum Brook near Sandusky, Ohio. Nobody knew it at the time but that internal staircase was going to make trouble. In a downwind configuration, with wind blowing through the tower to reach a blade, interior stairs would cause turbulence and uneven blade loading. The remedy was to remove the stairs completely and use a cable elevator to provide access to the nacelle.





With crane and riggers at the ready, the complete power unit and blades of the Mod 0 machine are prepared for their perch 93 feet aloft. Although far smaller than the giant machines yet to come, this 100 kW turbine would test and measure many new engineering and design features. Data derived from extensive instrumentation here would be influential in the design and materials choice for more sophisticated turbines now supplying multimegawatt power to utility nets. Much modified, Mod 0 is still at work on many development studies.

There was only one choice. The NASA team moved immediately into full-scale design and development of a 100-kilowatt-plus wind-turbine system. The machine would be installed at the Plum Brook facility about 60 miles away, making that station the first of many to become pioneer sites for testing large wind turbines. It took eighteen months, but it unleashed a flood of knowledge.

The first Plum Brook installation, designated Mod 0 and with a rated output of 100 kilowatts, went up in September 1975. The machine would cut in and begin generating power when the wind reached 9 m.p.h. By 18 m.p.h., it would be developing a full 100 kilowatts, and at 40 m.p.h. it would cut out. Later machines would operate at higher wind velocities.

It was awesome and inspiring, particularly to the engineers who knew they would learn from Mod 0. Its 100-foot open-truss tower even had an interior stairway, eleven zigzag levels to allow access to many critical parts of the system—the rotor hub and attachment points between blade and shaft, the gearbox, the myriad instruments and support equipment to monitor operation, and the generator itself.

Six years after that first machine—a giant for its time—was installed at Plum Brook, Mod 0 remains in heavy use. But now the 100-kilowatt turbine looks small. Compared to the new generations, all tracing lineage directly back to Plum Brook, this open-truss tower resembling an oil derrick, with its bullet-like nacelle and 125-foot blades, is an oldtimer.

"But it's still our primary technology development tool," Baldwin explained with an old-hand's pride. "Since 1975, the Plum Brook installation has had a dozen major configurations and maybe seventy minor ones."

In addition to trying out new designs and concepts, Mod 0 has validated a complex computer

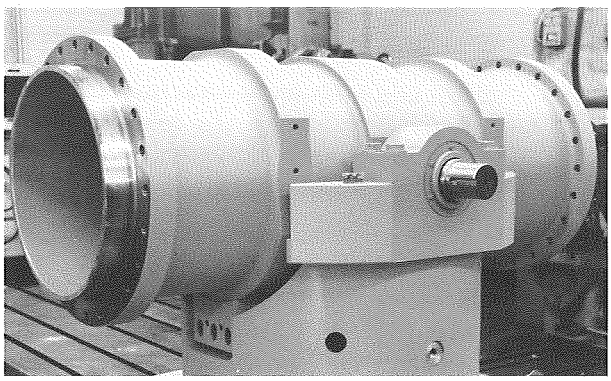
code that is used to model turbine dynamics. To get that code, NASA went to the Paragon Pacific Corporation, noted for its experience in helicopter blade dynamics. The company spent several years perfecting the intricate programming that now allows a computer to combine dozens of variables in wind, turbine design, thermal properties, and much more to calculate wind-system dynamics. Called MOSTAS, that software now is in the public domain for use by wind-turbine designers. Improvements are still being developed to evaluate advanced concepts and to improve the accuracy of computerized predictions.

When Mod 0 is running, the power it generates is synchronized to feed into the facility's electrical lines, or to feed directly into the Ohio Edison grid. That benefit is small compared to the knowledge it generates, both when it is working smoothly and when it isn't. The most important lessons come from analyzing problems and finding solutions, Baldwin said.

In its half-dozen years, Mod 0 has been the test bed for all variety of concepts. Its blades have been steel, aluminum, fiberglass, wood, and hybrids. The tower has been rigid, anchored solidly at its base, and then "soft," with the tower resting on heavy leaf springs that give just a little in the wind. As the testbed for the soft-tower concept, Mod 0 demonstrated that soft towers have a lower natural frequency than the rotor, and thus are less likely to set up fatigue-inducing harmonic vibrations.

It also has tried and tested fixed hubs, with a rigid attachment between blade and power train, and teetered hubs that let the blades shift just a bit if wind conditions are inconstant. The proof-of-concept testing for soft towers and teetered hubs paved the way for both innovations to be incorporated into turbines beginning with the advanced Mod 2 machines.

From the beginning, Mod 0 was a downwind machine, with the wind going past and through



An experimental teetered hub, designed for use on the Mod 0 100 kW machine. Similar ones are now in general use on bigger turbines, allowing the blades to move up to 6 deg. in or out of the plane of rotation. This reduces stresses and allows the assembly to accommodate transient loads imposed by gusts. Hub construction is husky because loads are high.

the tower to reach the blades. But it also has been an upwind testbed. Upwind turbines face into the wind, which passes first through the blades, then through or around the tower. There are advantages to both concepts.

Upwind machines get the wind pure and unsullied, with no turbulence created by passage through the tower. With truss towers and rigid hubs, steady bending loads on the blades are higher, cyclic bending loads are lower. But upwind machines require yaw control. The natural tendency is for the blades to pivot away from the wind. A mechanical or hydraulic system is needed to keep those blades aimed into the wind. Further, the system must accommodate those capricious changes in direction that make winds so unpredictable. Upwind efficiency is slightly greater and can yield improved annual power production.

Downwind turbines tend to free-yaw, steering themselves to match the air movement. They can find their own equilibrium, pivoting to maintain the direction needed for wind flow over the blades. This self-adjusting yaw tendency makes it possible

for downwind machines to be somewhat less complex and thus less expensive. To minimize loads imposed by veering winds, designers nevertheless provide some degree of yaw control on big downwind machines.

That same wind passing through the tower can be a villain. Ron Thomas and the NASA wind team discovered that fact early in the testing program. Almost from the beginning of Mod 0 operation, something was wrong. The blades developed higher cyclic bending loads than expected. Dire problems were feared, Baldwin recalls. With a relieved smile and a hefty dash of engineering chagrin, he explains that it was all caused by those interior stairs! They created such air resistance, causing a combination of turbulence and discontinuities in the wind flow, that the blades simply couldn't perform as designed. With each revolution, they were being subjected to intermittent stresses well above predicted levels. In addition, loads were amplified by a chance resonant frequency match with the yaw drive.

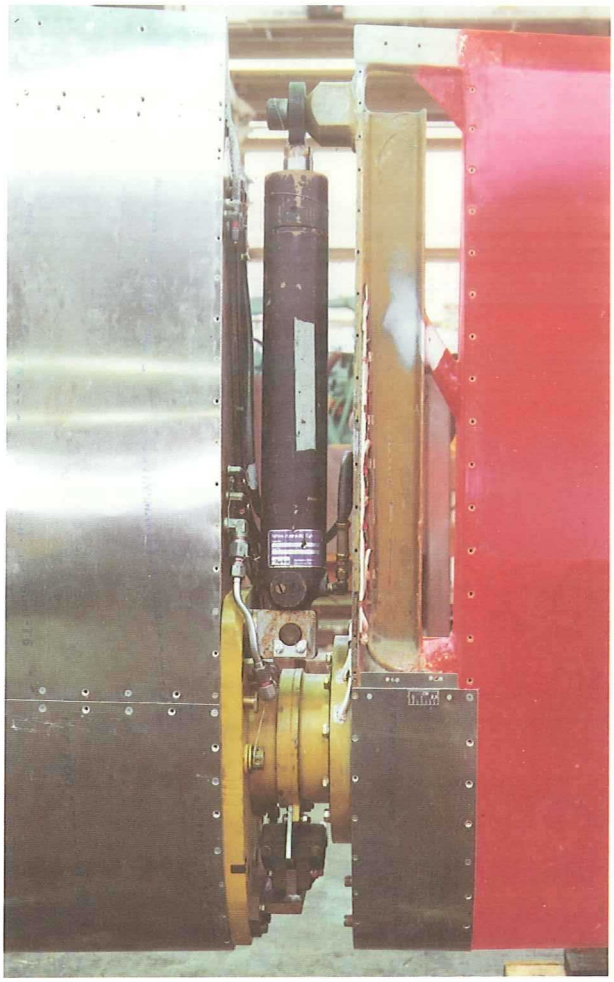
The problem had seemed severe. The solution was simple. Out went the stairs, in went a cable-hung platform elevator. The yaw drive was stiffened, and the Plum Brook machine began to perform as hoped. It was an early lesson in mastering the tricks of wind energy, one that wasn't lost or forgotten on future machines. Without exception, turbine towers today are stairless. Acrophobic visitors have a choice: close their eyes during the ride to the top on the open-sided elevator, or stay on the ground. Another lesson: dynamic couplings among the rotor, nacelle, and tower are now carefully analyzed to prevent any resonant frequency matching.

As a wind-turbine technology development tool, Mod 0 has no equal. It has contributed much new knowledge to the field and its findings have led directly to major economic and engineering improvements in the systems that followed. Among scores of tests conducted with Mod 0, some major concepts have been examined.

- Interaction between a wind turbine and utility networks has been examined from virtually every angle. Mod 0 has successfully fed power through a load bank, a diesel generator and load bank combination, Plum Brook's onsite network, and into the Ohio Edison grid. The variety of tests and their results yielded procedures for smoothly synchronizing a wind machine with a utility grid, and demonstrated that automatic operation of a wind turbine is both feasible and realistic.
- Environmental problems, including noise and television interference, are minimal, but also partly dependent on individual wind-turbine siting. Noise from Mod 0 is not troublesome and is virtually indistinguishable from background noise beyond 800 feet. Only one installation would later suffer from a significant noise problem. The Mod 0 tests showed only minor television interference, but it would be enough to require corrective action at some locations. In no case did the Mod 0 wind turbine, or any other turbine, have an adverse impact on wildlife, including birds.
- Starting, stopping, and controlling the speed of wind turbine blades, particularly stopping them in high winds, was largely accomplished by changing the pitch, or angle of attack into the wind, of the entire blade. Mod 0 tests proved that controllable blade tips did the job just as well, while reducing the complexity, and the cost, of control systems.
- Drive-train tests proved that use of a fluid coupling in the high-speed drive train reduces both fluctuations in alternator output and dynamic loads. Step-up gearing is needed to match the difference between moderate propeller

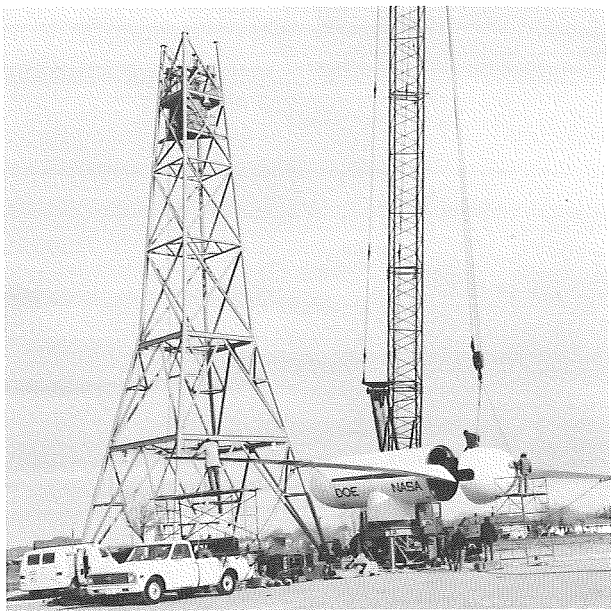
speed, to keep bearing loads and tip speed within limits, and generator characteristics, which require high speeds, typically 1200 or 1800 r.p.m., to match grid frequency.

NASA decided early that Plum Brook would remain the site of experimentation, but that other turbines must be installed in routine, useful, geographically diverse situations. No turbine site other than Plum Brook would be operated by NASA itself. Instead, the Government would select local utilities, some small, some enormous,



Steerable blade tips, pivoted by hydraulic cylinders, proved as effective as feathering the whole blade. In view at right, note actuator that adjusts the tip's angle of attack.

Sensitive control of turbine output, from complete stall to full power, is achieved by changing the pitch of an outer segment of each blade. Blade attachment at the hub of the rotor is simpler and stronger. Not all turbines use tip control.



Out by the fair grounds in rural Clayton, N.M., a Mod 0A 200 kW turbine grew to be a local attraction. One finding: major modifications or repairs had to wait on the arrival from out of town of a large motorized crane.

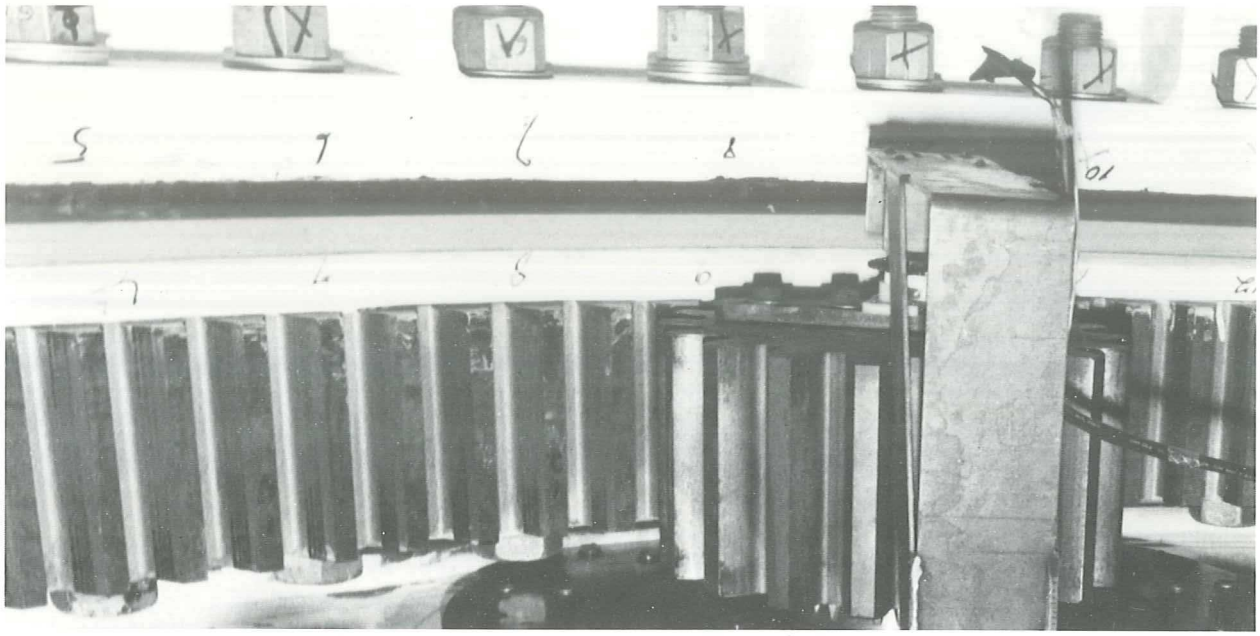
to take responsibility for individual turbines. The machines would be designed and built with Federal funds. Installation and whatever follow-on troubleshooting that was needed also would be included. But if wind turbines were to become an important element in electrical generation, they must be tied to local utilities, operated locally, a accepted generating source.

The calls for utility volunteers went out. The responses came back with vigor and the Mod 0A machine came into being. Each site would have computerized monitoring equipment to gather and correlate data. Built by the Westinghouse Electric Corporation, the Mod 0A is a downwind turbine rated at 200 kilowatts. Its cut-in wind speed is about 10 m.p.h. at hub height, with full power developed at 22 m.p.h. When winds exceed 40 m.p.h., the blades feather and the turbine cuts out. At this stage of development, the cost of electricity produced was considered to be less important than proving the engineering. Depending on the mean wind speed at sites selected, electricity generated by a Mod 0A machine could cost from 30 to more than 35 cents a kilowatt-hour. Under the best of circumstances, Mod 0A would run a financial deficit. The experience such machines would provide would be more than worth that cost.

One after another, the lessons learned on Mod 0 found their way into the Mod 0A machines. Four of them were built and installed, first at Clayton, New Mexico, then successively at Culebra, Block Island, and Oahu. Each unit benefited from the one before, and from ongoing tests at Plum Brook. Each spent less time awaiting repairs and more time generating electricity.

Experiences at each Mod 0A site varied. None went problem-free and, as might be guessed when local conditions are so different, some had considerably more trouble than others. The Clayton machine was installed in November 1977, followed by Culebra in June 1978, Block Island in May 1979, and Kahuku Hills on Oahu in May 1980. Easily the most successful was the Hawaiian machine, benefiting from earlier lessons learned at other sites and in addition enjoying the steady thrust of the trade winds to increase total electrical output.

Among the repeated troubles experienced at Clayton, Culebra, and Block Island were blade fatigue stress cracking, hydraulic failures, burned-out generator bearings, fluid-coupling leaks, and yaw-control system malfunctions. In every case, problems were identified, isolated, and corrected. In some severe cases, particularly when blades were



Pointing a big turbine either into the wind or downwind, depending on design, isn't left to chance, although downwind machines are somewhat self-adjusting in yaw. Above, in a big Mod 2 machine, a large ring gear is turned according to signals sent by a wind vane to a hydraulic motor.

Profiting by the experience of earlier turbines, the Oahu Mod 0A machine did consistentiy well for a year and a half. An ambitious, privately funded wind farm of turbines is planned nearby.

involved, turbine shutdown could extend for months. In other cases, it was a matter of hours or days before the machine would be up and running again.

Culebra experienced a number of minor problems during 1979 and 1980, causing frequent shutdowns resulting in decreased power production. A recurring overspeed condition, leading to automatic shutdown, was traced to nothing more than loose belts in the mechanical controls. But leaky pitch-control seals took longer to replace. Other troubles were traced to Culebra's tropical climate. Fungus growing in the control system led to internal electrical problems. Spores found their way onto a microprocessor chip, where they shorted out microscopic circuitry. Then corrosion in the connections with the utility triggered several high-voltage shutdowns. Though such climate-induced problems had hardly been foreseen, none was difficult to cure. Again, the lessons were plain; future

wind turbines destined for humid and tropical sites certainly will include the minor modifications that are indicated.

Block Island's experience has been a little different. Isolated about 25 miles off the coast of Rhode Island and Connecticut, it is home to only a few hundred year-around families, but can have ten times that population at the peak of the summer season. Its local electric utility is diesel-powered, with ten generators that swallow fuel priced at more than $1 per gallon delivered. Result: The residential rate for electricity was between 22 and 23 cents per kilowatt-hour in 1980. The Block Island Power Company responded to NASA's request for proposals from utilities interested in wind power and was accepted.

"It's great, it's wonderful," was the enthusiastic endorsement of Merrill Slate, the power company's vice president and general manager, in the autumn of 1980. By that time, the turbine had been in operation, or partial operation, for more than a year. "I don't know how much fuel it has saved us yet, but last winter we averaged 35 hours a week of operation.

"Sure, we have problems. The biggest one is probably logistics. Right now, we've been down for two weeks just waiting for a little 2-h.p. motor

At Block Island (below) as at Oahu, the Mod 0A developmental machines have been the beneficiaries of not only steady ocean breezes but also interest in an alternative to high fuel costs. Here the operating experience has been generally good except for TV interference in the compact community; a cable system had to be installed. But anything that decreased the consumption of high-priced diesel fuel was welcomed by those who paid the power company's bills.

to get here. You never know. A motor like that should go forever, but that's the second one we've lost. A little thing like that puts the turbine out of business when you're as isolated as we are."

Even when the wind is up and the turbine operating, several diesel generators must be running. Peak electrical demand on the island comes between July Fourth and Labor Day, and averages about 1400 kilowatts, whereas the winter load comes to an average of about 400 kilowatts, but at best, the wind turbine supplies just half of that. At least one backup generator is kept running—and burning that expensive diesel fuel—when the turbine operates, to take over quickly if the wind dies or if some turbine problem causes an automatic shutdown. The backup generator runs at about 50 percent power, Slate explained, because lower power causes a black, wet exhaust and increases the chance of a smokestack fire.

Other problems at Block Island are more directly related to the wind turbine itself. The most troublesome was television interference that had local citizens in an uproar. In the compact community, with most residents living close to the turbine, the spinning blades chopped TV signals to an irritating degree. The Department of Energy resolved the dilemma by footing the bill for installation of a cable television system. It seems almost certain that any future wind turbine installed in midst of a community will face a similar problem and require a similar or possibly some other solution.

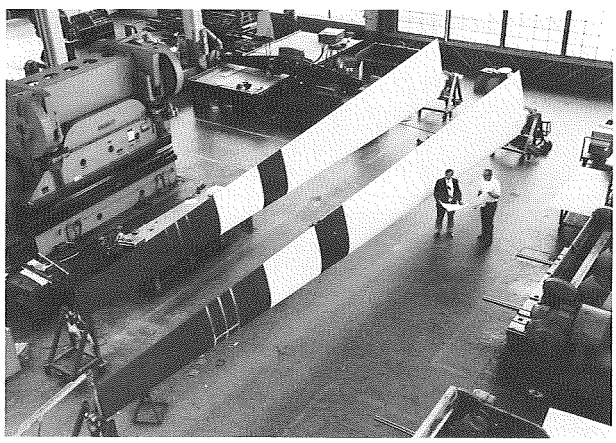
"Except for the television interference, local reaction is totally positive," Slate said. "Anything that will lower the light bill has our support."

Within the wind-turbine system itself, troubles cropped up in the form of fatigue cracking at rivet holes in the aluminum blades and in the way the microprocessor control was reacting to certain mechanical switching. "NASA sent out laminated wood blades that seem like a better design," Slate said. "We're producing 10 percent more power at low wind speeds with the new blades, getting electricity with winds as low as 7 or 8 m.p.h.

"The NASA people traced the switching problem to a voltage surge whenever the mechanical switch came on. The microprocessor read the surge as trouble and would shut everything down again. Now we've gone to full microprocessor control on the switching and everything's fine."

At the end of 1980, the Block Island wind turbine was turning in a superior performance. Nearly a year newer than the Culebra turbine—and thus benefiting more from the growing base of experience and technology—it had generated nearly as much energy as its Puerto Rican cousin, 201 megawatt-hours total to 250 megawatt-hours. More important, with a great many problems

Far from simple, the blades of a large wind turbine draw on aeronautical theory and experience as well as materials know-how and stress analysis. These are comparatively small 62-footers made for use on the Mod 0 100 kW machine.



resolved, and taking advantage of the Atlantic's winter winds, the Block Island machine produced an amazing 18.83 megawatt-hours in the last two weeks of the year alone.

"The project's advancing," beamed Merrill Slate. "Anything takes time to perfect. It doesn't matter if it's a car or an airplane or a wind turbine. It just takes time to get it right."

Private industry agrees. The Electric Power Research Institute (EPRI), located in Palo Alto, California, is the non-profit research arm of the electrical utility industry. A 1980 EPRI report, prepared by the Arthur D. Little company, assessed the state of large wind-turbine technology in the United States, with particular emphasis on the DOE/NASA program. The investigating team had "timely access to much of the data and information emanating from Federal field tests of large wind hardware and is in a position to make a relatively independent assessment." Included in the report was a detailed evaluation of the first eighteen months of operations at the Clayton, New Mexico, Mod 0A turbine, the first of the series.

Clayton is a rural community of about 2900 on the high plains of northeastern New Mexico. The city-operated Clayton electric system is not interconnected to any outside power source. All electricity used in the town was locally produced by diesel or natural gas generators. Peak loads of about 3200 kilowatts occur in the winter, when days are short and icy winds sweep out of the Rockies, but because of the community's climate and stability, that peak is only slightly higher than the average year-around peak load. Clayton's isola-

Experimental stub blades tried out at Clayton after the original aluminum ones consisted of 40 feet of wood laminate ending in 6 feet of fiberglass. They worked well, paving the way for highly successful laminated-wood blades.

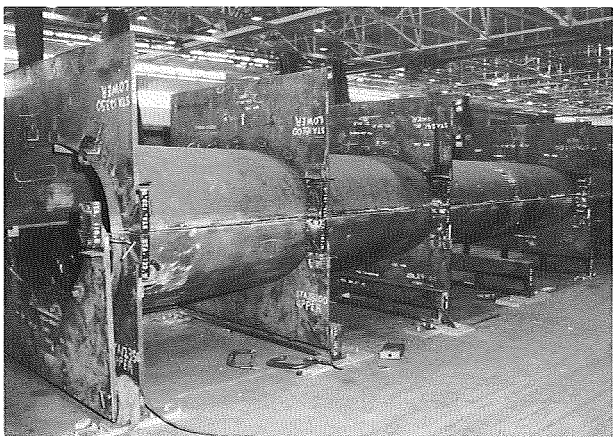
tion, independence, and wind regime made it an ideal candidate for the program's first field installation. The 200-kilowatt machine was erected in November 1977, and after synchronization and about 100 hours of burn-in time to verify operation, began operational testing by the municipal utility in March 1978.

From that moment, the Clayton Mod 0A became both teacher and pupil in an inanimate technological sense. As the first field installation, it was an experimental learning tool, teaching the intricacies of turbine operation to NASA engineers, their Westinghouse counterparts, and the utility technicians who carried the day-to-day responsibility for running the machine. Moreover, it was (and is) a testbed for improvements and modifications in routine utility use.

True to form, the Clayton machine had good days and bad. But to the delight of virtually everyone involved in the program, Clayton's big windmill was an immediate hit with the townspeople. Placed on the outskirts of town near the county fairgrounds, the turbine quickly became Clayton's leading attraction. Residents proudly toured visitors around the huge machine. When it was operating on pleasant evenings, they were apt to bring out the lawn chairs, ice chests, and even knitting to gather in neighborly groups, sit in the warm twilight, and chat, while nearby their very own wind turbine towered above, its 125-foot rotor turning with a quiet whoosh . . . whoosh . . . whoosh. In officialese, the Clayton wind turbine "found public acceptance." But it did better than that. The people not only were proud of their machine, they loved it.

Even when it didn't work.

EPRI examined the first eighty-six weeks of Clayton operations in minute detail. In that lengthy period, the machine produced 493 mega-



Curved steel plates will be welded to form a load-bearing spar for an immense Mod 1 blade. Foam plastic covered with stainless-steel sheeting gives it its final aerodynamic shape.

watt-hours of energy. But for prolonged periods, it didn't operate at all. "During the period of interest the machine was inoperable or saw very little operating time for eighteen weeks," EPRI reported. "This resulted from service delays or delays associated with spare parts." Clayton's technical problems fell into categories: (1) unreliable components, (2) assembly or repair, and (3) delay created by difficulties in getting a large crane into a remote location. That problem is likely to be encountered whenever wind-turbine systems are installed or undergo major repairs involving blade removal or generator changeouts.

It was exactly the kind of technical information revealed by Clayton's troubles that NASA and DOE sought. The first major warning flag went up only a few weeks after the municipal utility took over turbine operation. The turbine's long blades were aluminum skin and ribs, attached to the hub with a steel spar. Employes heard a creaking noise that seemed to come from the turning blades and soon spotted gray discolored areas around some

protruding fasteners. A call to the Lewis Research Center brought a NASA inspection team.

The team found structural damage at the root ends of the blades. Because there was no immediate danger to the system, it was allowed to resume operation until temporary replacement blades could be shipped. In June, the machine was shut down for three weeks for blade exchange. Inspection of the original blades at Lewis revealed two design deficiencies not previously suspected. A line of fasteners along the trailing edge of the blade could not carry the actual shear loads encountered. Some fasteners broke or worked loose, and some ribs developed cracks. In addition, investigators found excessive rubbing at a bearing interface between the steel blade root and an aluminum rib.

"Our goal in those years was to get a blade that worked, without too much regard for cost," said blade expert Pat Finnegan at Lewis Research Center. "Once the design problems were solved, we could concentrate on reducing the price."

The Clayton blade was typical of early difficulties. "We learned that the key to design was getting the loads through the blade and into the hub," Finnegan explained. "Early on, we had rivets popping, cracks, wear and tear, all usually showing up in the first 600 hours of operation."

But none of the problems was fatal to wind-turbine technology. Fixes proved relatively simple—reinforcements at crucial stress points, a redesigned bearing, a modification in blade attachment points. In addition, a special ring liner was bonded to a rib getting extra stress and steel shims were inserted. By September 1978, the original blades were back at Clayton. The machine was shut down for another two weeks while they were reinstalled. For nearly seven months, with the exception of a week in December when a burned-out generator bearing was replaced, the turbine operated with only these minor problems:

- Ice buildup on the blades triggered frequent winter shutdowns, partly because an ice detector was simply set at too sensitive a level.
- Periods of low wind followed by periods of stormy high winds resulted in non-operation.
- The turbine's yaw system malfunctioned, a fluid coupling failed, and a pitch-control wire broke.

Yet through the winter, nothing in the turbine's operation made drastic difficulties. Problems were noted and handled, procedures were modified so as to be ready for next time. But there was continued concern about the blades. Periodic inspections showed that the special ring liner had loosened and that shims needed occasional adjustment. By April 1979, when the repaired blades had accumulated more than 3600 hours of operation, increasing damage in the areas repaired earlier forced NASA to order another shutdown. Replacement blades were not immediately available and it would be ten weeks before the Clayton wind turbine turned again.

In bringing wind-turbine technology from concept to operation, problems with blades and other major components are expected. The aluminum and steel blades installed at Block Island had fewer problems than did the Clayton blades. "By the time the third set of blades was produced by Lockheed, the manufacturer, we had all the modifications done in advance," Finnegan recalled. "That set was installed at Culebra and by the end of 1980, we had more than 2000 hours of operation with no major problems."

If the big difficulties were anticipated at Clayton, one peripheral complaint was not. Reported EPRI: "The greatest objection. . . by Clayton utility personnel is that the machine is not automatic

This blade is part of a part: it will become the outer 20 feet of the 45-foot steerable tip at one end of a 300-foot Mod 2 wind-turbine rotor. Skin and rib construction is employed, the skin here being steel 1/8 inch thick. In midsections of the rotor the skin is 1/2 inch thick; the hub section uses steel no less than 1½ inches thick. Great strength and stiffness are needed in a rotor that generates power roughly equivalent to 3350 horsepower when turning at its full rated load.

enough . . . a large number of safety-system shutdowns have occurred, requiring that a local utility person manually reset the WT [wind turbine] each time. These shutdowns have been the result of two problems: the failure of specific components, and tight safety tolerances aimed at protecting the machine. As more machine familiarity and component screening methods are developed, reliability is expected to improve. In addition, once the machines advance beyond the prototype test phase, it will no longer be necessary to constrain the machine's safety parameters so rigidly.''

Using Clayton for its first in-depth examination of utility-scale wind-turbine operation, EPRI emphasized that usefulness to the industry is its primary concern. The initial findings were favorable. ''Test results to date have validated the DOE/NASA WT design procedures which have been established by both supporting research and technology and sound engineering programs,'' the report said. ''Cost of energy projections indicate that later-generation WTs are likely to provide electricity at competitive costs in some utility systems within several years.''

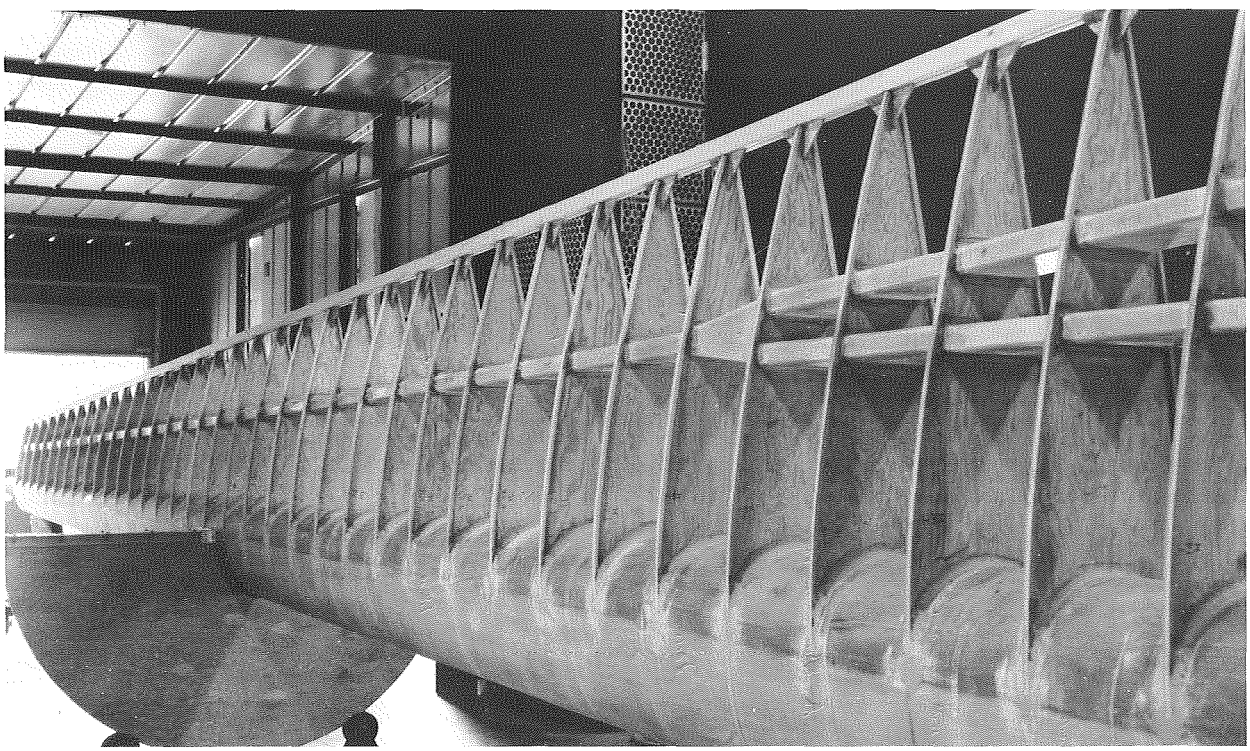
The final Mod 0A machine went into operation in Hawaii in mid-1980. Gone are the metal blades and in their place are superior wood blades with better aerodynamics, less weight, greater resistance to stress fatigue, and having a high potential for long life and lower cost in production. Identical blades have since been installed at Block Island and Culebra.

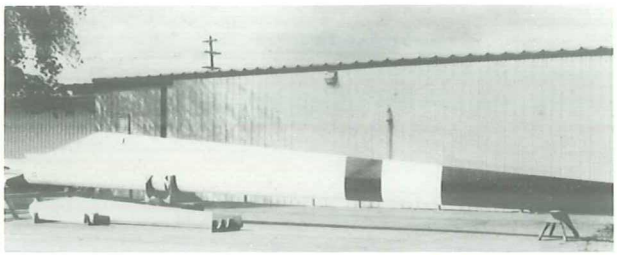
"We pushed ahead with our low-cost blade development," Finnegan said, "and the leading candidates were blades of fiberglass, steel, steel composites, and laminated wood. The wood blades are based on boat technology and came along fastest and cheapest."

Built by Gougeon Brothers of Bay City, Michigan, the 62-foot blades installed at Block Island and Hawaii are built up with layer after layer of fir. The effect is much like plywood, but here there are 74 layers of fir at the blade root, tapering down to just eight layers at the blade tip. Fir strips are glued, bonded with epoxy resin, and then the blade is bagged and vacuum cured. With various cutting methods tried, NASA and Gougeon settled on a procedure that will produce wood blades at a cost of less than $5 a pound. Early aluminum blades cost up to $100 per pound.

But wood is not the only answer, particularly for the largest wind turbine envisioned. "In the future, all of the blade materials used may have a role," Finnegan predicted. "The blades for the big Mod 2 machines are steel, an inch-and-a-half thick tapering down to one-sixteenth of an inch at

In an example of engineering ingenuity, the spar making up the leading edge of this experimental Mod 0 blade was originally a steel utility light pole. The plywood ribs were later covered with an impregnated fabric. It worked well in tests.





Above, the Gougeon laminated-wood blade, built up from epoxy-bonded layers of fir, has performed well on 200 kW Mod 0A turbines, proving to be strong and inexpensive.

The Boone turbine at right, a ten-times scale-up in power from 200 kW to 2 MW, wasn't troublefree. The blades caused some television interference, and for a while they also created a local low-frequency thumping sound.

the tip. We may see future modifications with fiberglass or wood for those steerable tips.''

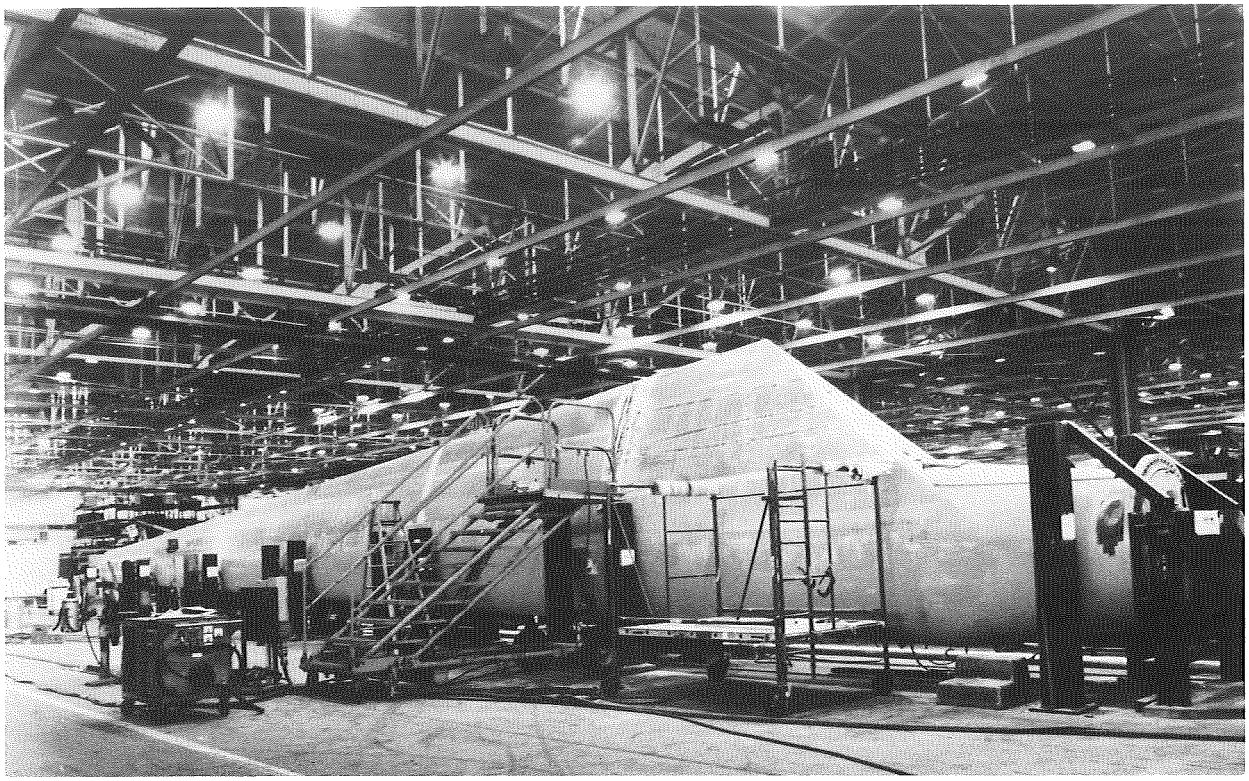
That change alone could cut more than three tons from the weight of a very large blade, Finnegan said. Then there are the composite blades just coming out of prototype production in 1981. Such blades, using fiberglass and epoxy resins, will require long-term testing under actual utility conditions, just as did earlier blades. But initial projections for their cost and effectiveness are optimistic, according to Finnegan.

Hybrid blades may play significant roles in the future. In late 1980, blades tested on the Mod 0 at Plum Brook had a hollow steel ''utility pole'' spar, spruce ribs, and a fiberglass cover. They cost about a seventh of the original aluminum and steel blades.

By early 1981, Mod 0A's wood blades—costing a scant fraction of the original blades—had proved to be winners. In barely more than a half-year of operation, the Hawaiian wind turbine had far surpassed the power production of both Culebra and Block Island, and was rapidly closing on Clayton's all-time record. The Hawaiian unit produced 439 megawatt-hours in that half-year, averaging 147 kilowatts for every hour of generation. Within months, Governor George Ariyoshi announced a privately supported $350-million program to establish an Oahu windfarm producing up to 9 percent of the island's electricity by 1985.

Overlapping the Mod 0A testing is the single Mod 1 machine in the program, the 2-megawatt giant (later downrated to 1.5 megawatts) on Howard's Knob in Boone, North Carolina. Then came the Mod 2, the sleek trio of 2.5-megawatt turbines at Goodnoe Hills, Washington.

Mod 1 was developed as a ten-time scale-up of the Mod 0A machines. It was the Federal wind-energy program's first venture into the really big machines that will be needed by the nation's largest utility systems. With General Electric as the prime contractor, the DOE/NASA team set out to get early experience with a multimegawatt wind turbine interconnected with a local utility, the Blue Ridge Electric Membership Cooperative. Unlike utilities cooperating in the Mod 0A effort, Blue Ridge had no generating capacity of its own.



The welded steel spar shown being built up on a previous page, with plastic foam covered with stainless-steel sheeting for an aerodynamic shape, is the core of this giant wind-turbine blade. With its twin, the blades are designed to extract up to 2 MW of power from the wind near Boone, N.C. Experience revealed that the blades were sometimes noisy thumping through air turbulence downwind of the tower. Reducing tip speed from 250 to 165 mph helped considerably.

It purchased and distributed electricity from Duke Power. The Mod 1 machine, with its 200-foot steel spar rotor and 131-foot open truss tower, would become its only generating facility.

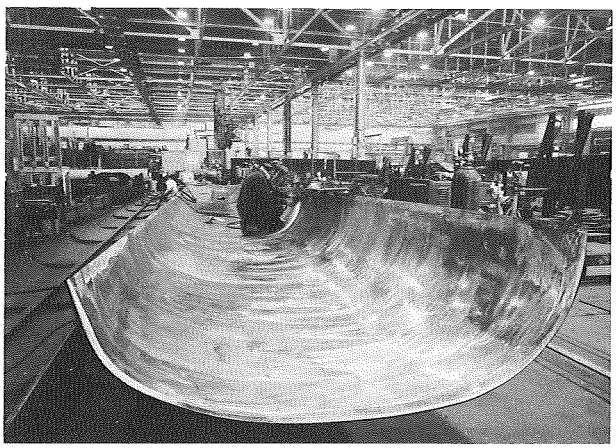
Howard's Knob, pine and hardwood covered, the city of Boone, North Carolina, at its base and up its flanks, surrounded by small ponds and a number of residences and small neighborhoods, was selected for the Mod 1 installation. At this bulge of rock in the western part of the state, the winds blow strongest at night as currents are born and gather force from the unequal cooling of Blue Ridge peaks and valleys.

First rotation of the 2-megawatt downwind machine came virtually on schedule in May 1979, and test operations began soon thereafter. Shortly after, Mod 1 encountered two problems that would create a ripple effect of modification throughout every large turbine on the drawing boards.

The first telephone calls to the utility were more curious than angry. When the blades turned, as they were most apt to do during prime-time evening hours, some nearby television viewers found their pictures flip-flopping, with interference lines of buzzing static crossing the picture.

"We knew at the outset that television interference was a potential problem," explained NASA's Darrell Baldwin. "Our work at Plum Brook showed the effect could reach out one or two miles, particularly when the wind turbine is directly in the line of sight between a television station and the receiver."

But the scale-up at Boone sent waves of interference affecting about twenty homes. The complaints became louder and more frequent. The easy solution, don't run the turbine during television prime time, was just a stopgap measure. It quieted complaints, but didn't solve the problem. NASA tackled the problem, evaluating a variety of proposed solutions, ranging from providing high-gain antennas to affected homes, to rebroadcasting signals, to extending an existing cable system (such as



Welded lengths of curved steel plate are the beginning of what will be the spar within a Mod 1 blade. While it seems massive, loads will be large and constantly varying when the blade is exposed to the power of a gusting wind.

was done at Block Island). "One problem with using a cable is that it fosters the idea that wind turbines will require cable TV," Baldwin said, "but that won't necessarily be true. If we were to change to fiberglass blades, that would help. But we won't know until we get the field experience.

"One thing is certain. There will always be a major siting consideration with regard to television and electromagnetic interference."

While the television problem went on, a more critical phenomenon appeared. It was noise. Under some conditions, a shivering low-frequency, nearly inaudible sound washed downwind from the turbine. Windows in a handful of homes rattled, sleep was interrupted, and tempers got touchy.

Woosh-thrummm . . . woosh-thrummm . . . woosh-thrummm . . .

"All our experience indicated that noise wasn't a problem with large wind turbines," Baldwin said. "It was the scale-up at Boone that got us into trouble and really caught us by surprise."

Woosh-thrummm . . . woosh-thrummm . . . woosh-thrummm . . .

It took a while, but as experts swarmed over the Mod 1 site, recording, analyzing, measuring, and calculating, the cause of the noise was found. As so often with new technologies, it was a combination of factors rather than any single thing.

As Baldwin later reported, it involved everything from the speed of the blade tips to the wake of the tower legs to the location of the houses disturbed by noise. Because the rotor operates downwind of the tower, each blade passes through the wake of the tower legs on every revolution, and the sudden pressure changes on the blades created the noise.

"The tips of the Mod-1 blades were moving at 250 m.p.h., compared with 180 m.p.h. for our smaller Mod-0 blades, which were quiet," explained Baldwin. "Higher tip speed, more than twice the rotor area, and twenty times the power at Plum Brook combined to create much more noise." Worse, the houses affected the most were in small valleys near the machine. The valley sides shielded residents from normal wind noise but amplified sound from the rotor.

The engineers put their heads together, ran their calculations, and came up with a solution. "First, we slowed the blade to 23 r.p.m.," Baldwin said. "This reduced the tip speed to 165 m.p.h. We replaced the generator with one that would operate at the reduced rotor speed. And we dropped the rating to 1.5 megawatts to reduce gearbox wear."

The modifications, completed in late 1980, seemed to do the job. "It turned out that downrating the machine causes very little loss of energy or operating time at Boone," Baldwin said. "The Mod 1 machine had been designed for an 18-m.p.h. wind site, whereas the average wind speed at Boone is about 12 m.p.h. We could even

Connecting a 90-ton Mod 2 rotor 300 feet long to a shaft 200 feet in the air takes steady nerves and coordinated teamwork. The radio relays commands down to the crane operator.

get slightly more annual production since this machine could run more hours per year.''

Atop Howard's Knob, General Electric development specialist Jim Brown looked over the giant turbine with evident satisfaction. ''The terrain conditions here are partly responsible for the noise,'' he said. ''The noise was propagated and maybe even amplified and concentrated into a small area. It's one of those things you just have to learn.''

Adds Baldwin, with no small irony in his voice: ''Avoiding noise will definitely be a design consideration from now on.''

Even as the Mod 1 problems were nearing resolution, an advanced-design wind-turbine system was being installed by Boeing in southern Washington. Called Mod 2, three of the 2.5-megawatt machines were being readied for the nation's first wind farm. At 8:30 p.m. on December 22, 1980, the 300-foot rotor of machine number one rotated in a gusty wind. Eleven minutes later the turbine system was synchronized with Bonneville Power's electric grid and the first Mod 2 at Goodnoe Hills had successfully met its initial testing requirements.

The route to Goodnoe Hills climbs north out of the Columbia River gorge, then turns sharply east again to parallel the Northwest's mightiest river. At the cutoff, a small wind turbine rotates in a farmyard, supplementing a rural family's electrical power. A dozen miles down the road, three more wind turbines now pierce the horizon. They are giants.

It is a winter day and the sky is brilliant blue. These Mod 2 machines, representing the latest step in large wind-turbine development, stand like white-spired sentinels at the topmost ridgeline of Goodnoe Hills. The spires are 200-foot tube towers, slender from a distance, but surprisingly massive close in. Their great size overwhelms visitors to this unique national wind-turbine test site. High at the tower top rests a rectangular nacelle housing a 2.5-megawatt generator and anchoring the 300-foot single span rotor. The nacelle cants back at 2 degrees, just enough to guarantee that the spinning blade clears the tower.

Goodnoe Hills attracted attention in 1976, barely a year after the planners at the Bonneville Power Administration in Portland got serious about wind energy. A string of wind-measurement

That rotor is as long as a football field from goal line to goal line, but experienced riggers can remove or connect it with little fuss. This is one time when strong or gusty winds are unwelcome, for the huge Mod 2 rotor can't be allowed to slew or swing. That cubical structure behind and below the nacelle is an oil tank for the speed-increasing gearbox.

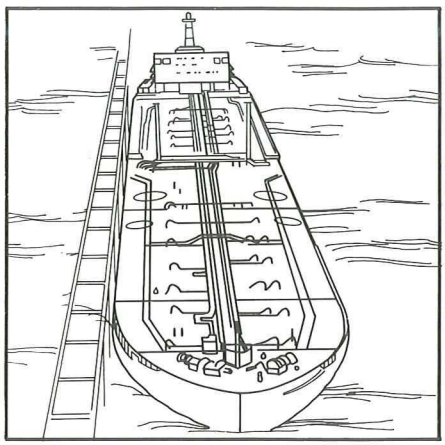
stations used by scientists from Oregon State University stretched for 100 miles along the Columbia Gorge and effectively bracketed Goodnoe Hills. With the Bonneville people now prospecting the wind, they selected a television tower at Goodnoe as a logical place for additional instruments. It was a fortunate choice, according to engineer Nick Butler.

"Topography is critical," Butler said. "Winds can change dramatically in only a few thousand feet. But we found what we wanted at Goodnoe." The site was selected for Mod 2 in 1979, two full years after Boeing had begun work on the turbine hardware itself. Capitalizing on the experiences of Mod 0A and the Mod 1 installations, and continuing development work on Mod 0 at Plum Brook, Boeing and NASA designed an upwind turbine with pitch control limited to the blade tip, and a hollow tube tower that is lighter and cheaper.

To help settle an open question on the effects of the interaction of multiple turbine wakes in the wind-farm concept, the three Mod 2 towers were spaced in a triangle with sides of 5, 7½, and 10 rotor diameters—1500, 2250, and 3000 feet apart. Instruments watch closely for any detectable interaction among the machines.

With the Mod 2 wind farm in operation, excitement and optimism for the program are growing rapidly. "We're approaching the point of having accomplished our primary mission," Baldwin said enthusiastically. "We're seeing an industry beginning to form. This has been a challenge for NASA, making sure that a complex technology is sound and can be transferred to the commercial world."

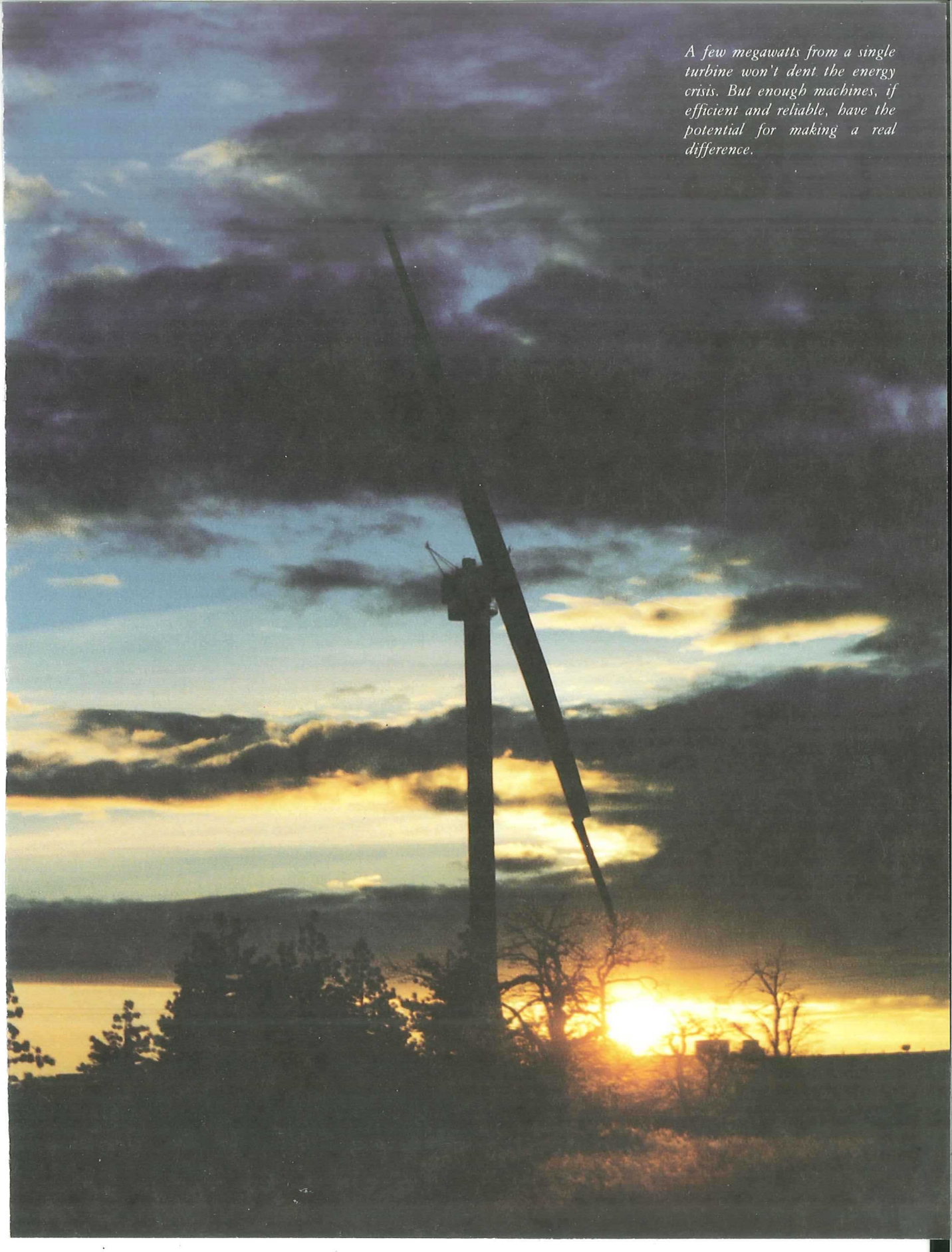
5
The Way the Wind Blows



The high cost of crude oil, along with the cost of antipollution equipment in coal-fired plants, has forced up the price of electricity. But wind is free and clean.

The tanker barely rolls in the gentle Pacific swells a mile off Dockweiler Beach. It sits deep in the water, filled to its deckplates with low-sulfur Middle East crude bound for generating plants in Southern California. Flexible hose pipes, large enough to swallow a man, hang over the gunwales and disappear beneath the water. On this afternoon in the mid-1980s, the tanker is alone at the offshore unloading terminal. Its 388 000 barrels of oil, a multimillion-dollar cargo, will be pumped ashore by evening. At midnight, the ship will weigh anchor and disappear into the ocean dark. The offshore roads will be empty. At sunrise, commuters along Vista del Mar will look beyond the breakers cresting on the beach and see nothing but blue Pacific to the horizon.

It won't last long. Another vessel soon will wallow in from the sea to empty itself into the onshore tank farm, then another, and another in an endless chain of ships plying the sea lanes from foreign oil fields to the coast of Southern California. To the north and south of Dockweiler Beach, the story is the same. At Long Beach Harbor and the Port of Los Angeles, at facilities north of Ventura, south of Oakland, and a dozen more, the oil-fueled utilities of the West Coast await their daily ration of imported crude oil. The two-way exchange of oil-in, dollars-out, goes on. But the rate of flow is changing. The serene, if infrequent, emptiness off Dockweiler Beach is a sight to behold for 1985 commuters. In the late 1970s, the roads were never empty. A tanker or two rolled at the hookup pipes day and night, with the next ship in line never far over the horizon. By the early 1980s, as energy conservation and price decontrol policies began to show effect, fewer tankers arrived. The offshore parking lot at Dockweiler Beach still was never empty, but increasingly just one ship anchored there.



A few megawatts from a single turbine won't dent the energy crisis. But enough machines, if efficient and reliable, have the potential for making a real difference.

The first of the big machines to pile up operating experience, the 2.5 MW Mod 2 may be a precursor of a new generation of working wind turbines. One advantage is that they can be more rapidly installed than conventional thermal or nuclear plants, creating revenue incrementally as they come on line.

At least a part of the reduction in foreign oil consumption during the mid- to late 1980s will be traceable directly to increased production of electricity through the use of renewable resources. Four potentially cost-effective wind machines were in consideration by mid-1981, though budget pressures tracked question marks across their schedules. The advanced Mod 5 wind turbines, with two versions on the boards, could be 5- to 7-megawatt machines that would set the pace for utility applications. Different, medium-sized machines, with broad appeal for small communities, military installations, and production plants, had reached engineering analysis.

But other large machines were off the drawing board, manufactured, and up and running. The first operational wind farm, established at Goodnoe Hills, Washington, under the Federal wind-energy program, had its three Mod 2 turbines synchronized with the Bonneville power grid in 1981, and were affording a glimpse of what may be in store for the future.

From the moment Boeing designers first set pencil to paper four years earlier, Mod 2 was intended to be a prototype of a commercial design. Rated at 2.5 megawatts in 27-m.p.h. winds, the machine's variable-pitch blade tips are microprocessors controlled to feather automatically as winds increase. The innovative tip control was first tried and proven on Mod 0 at Plum Brook. Now in operation at Goodnoe Hills, the system was programmed to shut down the turbine when the wind at hub height reached 45 m.p.h.

With installation and initial testing complete, the Bonneville Power Authority took over the Mod 2 wind farm operation. Remotely monitored through a console at BPA's computerized control center more than 100 miles away, the wind farm's normal operation is fully automatic. The prototype wind farm has been watched with more than passing interest by public and private organizations alike. Among them is the Department of Interior's Bureau of Reclamation.

In a unique project to explore the benefits of combining wind energy with hydroelectric power,

Reclamation contracted with Hamilton Standard for a 4-megawatt wind turbine to be installed near Medicine Bow, Wyoming. The machine will be the world's most powerful. In the meantime, Reclamation has prepared preliminary plans for expanding the Medicine Bow site into a wind farm. They have already funded a project to add a Boeing Mod 2 turbine for comparative testing. As many as forty large machines may be installed there. As with the program sponsored by the Department of Energy, NASA's Lewis Research Center provides technical management.

The Bureau of Reclamation began to examine the wind's potential in the late 1970s, seeing wind energy as a way to save water stored up behind its hydroelectric dams. Engineering analyses suggest that the two energy sources can supplement each other very effectively. Medicine Bow, Wyoming, seemed an ideal location to test the idea. High average winds whip out of the Tetons and rush across the plains directly at the site where power could be tied into an existing grid that connects dams at Flaming Gorge, Glen Canyon, and other hydroelectric plants.

No Substitute for Experience

When the unforeseen occurs, a question almost inevitably arises: Should it have been foreseen? There is almost never a totally satisfying answer. In June 1981 an incident occurred at Goodnoe Hills, Washington, site of three giant Mod 2 wind turbines. These are 2.5-megawatt machines with 300-foot, 90-ton rotors. In a test of the emergency system, which had previously behaved flawlessly, one turbine "ran away," overspeeded, damaged some parts, and then shut down. Operation of the other two turbines was suspended pending an investigation.

Careful analysis revealed this sequence of events. The shutdown test called for a rapid change of angle of the 45-foot blade tips that govern turbine output. When the programmed shutdown sequencer commanded shutdown, the blade tips at first failed to feather because the hydraulic valves controlling them were stuck. But 2.5 seconds later the sequencer automatically disconnected the generator output from the utility grid. This took the load off the drive train and gearing so that the big rotor, essentially running free, accelerated from its normal 17.5 r.p.m. up to 29.5 r.p.m. The gearing spun the unloaded generator from 1800 r.p.m. to more than 3000 r.p.m., at which point parts seized and broke up. Vibration from this thereupon jarred free the sticking hydraulic valves, and the blade-tip feathering system brought the turbine to a prompt stop.

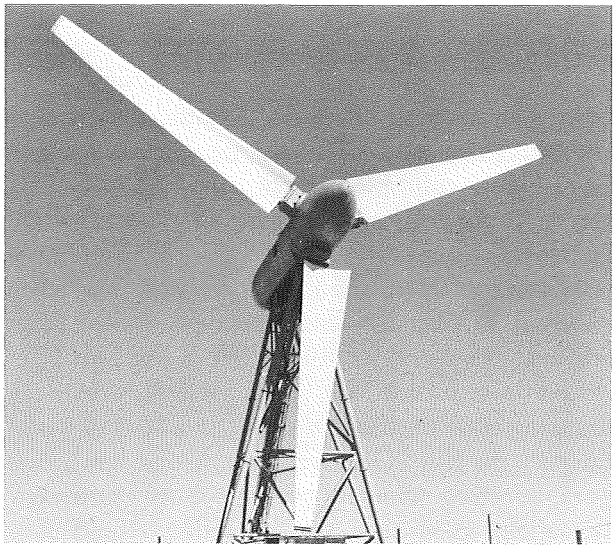
The trigger for the mishap was contamination of the hydraulic oil, fine enough to pass the 10-micron system filters and yet enough to cause the two redundant pairs of control valves to stick. Among the resulting changes were more rigorous procedures for handling make-up oil, and replacement of the valves with another design unlikely to stick. Sensors were also added to the valves to detect possible failures. Finally the shutdown sequencer was modified so that the load would not be cut free until output had dropped down to 5 percent of the rated level. With these changes made, two of the big machines were up and running in several months; the third, requiring replacement of some parts, was scheduled to come on line in early 1982. Under the brilliant illumination of hindsight, some onlookers wondered how the sequencer could have been allowed to drop the load so early in the shutdown. However, engineers accustomed to bringing large systems into service know that mishaps like this are the essence of development.—*F. Carl Schwenk.*

This thicket of reinforcing steel will be encased in concrete to form the foundation for a 3-MW wind turbine being built in Maglarp, Sweden. Except for a lower power rating, it will be a twin to the Hamilton Standard turbine in Medicine Bow, Wy.

More than half a continent away at Windsor Locks, Connecticut, the Hamilton Standard Company, working with the Swedish KKRV Company, was working on a 3-megawatt wind turbine for the Swedish government. The two-company team also bid on the Medicine Bow project, survived the rigorous technical evaluation by NASA's wind-energy team in Cleveland, and got the job in early 1980. Though similar to the machine destined for Sweden, the Medicine Bow wind turbine has a higher rated output and thus greater potential commercial application. Its fiberglass rotor is 255 feet long and the 4-megawatt generator is housed in a nacelle sitting atop a soft, tapered, hollow steel tower 262 feet high. The downwind machine is scheduled for operation in 1982.

Private utilities, in the meantime, moved ahead on their own. More than 120 miles inland from the cool Southern California beach breezes, hot desert and mountain winds whistle through San Gorgonio Pass. By 1985, in a scattering of vertical stands, gathered in grove-like patches of glistening steel and aluminum towers, the blades of four score or more wind turbines may be turning to generate multimegawatts of electricity into the grid of Southern California Edison (SCE). Sandwiched between the San Bernardino Mountains and the sprinkler-caused vapor haze over nearby Palm Springs, the windy pass was already in the early 1980s becoming a mecca for wind exploitation by private industry.

As early as 1981, a three-bladed Bendix turbine rated at 3 megawatts and a 500-kilowatt Alcoa Darrieus machine, both owned by SCE, were on site. More were coming. The Wecstech Company was preparing to bring in machines totaling 5 megawatts, with installation beginning in 1982. Capitalizing on the commercial potential of the



Southern California Edison has experimented with this unusual Bendix machine in Palm Springs. It originally had a hydraulic drive, and is now being converted to use a Mod 1 gearbox.

machines developed for Medicine Bow and Sweden, Hamilton Standard was planning to install and operate up to five of its giant 4-megawatt units between 1982 and 1984, adding another 20 megawatts to production. At the same time, SCE was evaluating other machines, including the Boeing Mod 2, with the intention of buying several more multimegawatt wind turbines itself for installation in 1982 and 1983. Other private developers, all eager to get into the wind-electric business, were negotiating with SCE. Among them was Wind Farms Limited, an entrepreneurial organization spawned by wind energy's early success.

As each new wind turbine goes on-line, whether owned by the utility or by company selling its power to the utility, the demand for foreign oil goes down. Private utilities, historically sensitive to the shifting winds of politics and economics, find

A record 4 megawatts is the power of this giant machine now being built for the Bureau of Reclamation at Medicine Bow, Wy. Its 256-foot fiberglass rotor, made by Hamilton Standard, turns downwind of the 262-foot "soft" steel tower. First rotation is scheduled to take place during 1982.

Snugging up a stay line on the 90-ton Mod 2 rotor is part of the delicate task of hoisting it up to mate with the drive shaft of the power train. That hand winch is secured to the blade of a front loader parked in a strategic spot.

themselves in the 1980s being sensitive to the wind itself. Southern California Edison is not alone.

In Solano County, just east of San Francisco, Wind Farms Limited signed an agreement with Pacific Gas and Electric to install 92 megawatts of rated wind power by 1984, with possible expansion to 350 megawatts by the end of the decade. While PG&E agreed to buy Wind Farm electricity, the utility itself had already become the first buyer of a Boeing Mod 2 machine. That 2.5-megawatt wind turbine was to be operational in 1982. The plan got a major boost from the State of California. The State Department of Water Resources agreed to buy the wind farm's off-peak production to help power the complex system that brings water through the High Sierra and into metropolitan California cities.

PG&E's plan for the decade calls for producing nearly 1 million megawatt-hours of power from wind by the end of 1989. With large utilities generally assuming that wind variability will cut annual yields to about a third to a half of rated output, the full PG&E windfarm could reach that goal, meeting about 1 percent of its customers' demands. Even that small fraction would save more than 1.6 million barrels of oil a year. "We think that any savings of oil is important," said PG&E's Charles Peterson. "What we're trying to get away from is the huge oil and gas burn that is so expensive and is the reason prices for electricity have been driven up so dramatically."

While PG&E was beginning site preparation in Solano County for its own Mod 2 wind turbine and for the wind farm to come, Wind Farms Limited was putting together Hawaii's first large-scale commercial wind turbine venture. In a $350 million package, the company proposed to install 80 megawatts of rated power in the Kahuku Hills area by 1984. Initial plans called for installation of twenty multimegawatt machines.

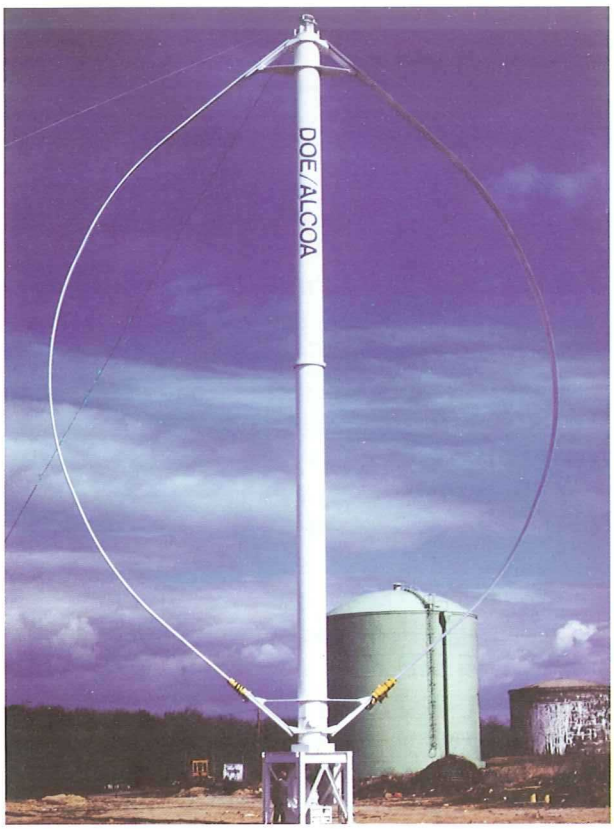
Indeed, the first seven years of effort put into the large wind turbine program had yielded more dividends than expected. But putting both hardware and concepts on the line at utility sites, the DOE/NASA team had left the talking and wishing behind. They set off down the riskier avenue of building and operating full-scale machines, to get the learning firsthand. The risk seemed to be pay-

ing off by the early 1980s, with a newly created wind-energy industry moving toward commercial success.

"You don't get confidence until you put machines up and run them," Alcoa's Paul Vosburgh believes. Alcoa moved into the commercial production of wind turbines in 1980 with three vertical-axis machines rated at 100, 300, and 500 kilowatts. A 500-kilowatt unit was installed for the American Public Power Association as a demonstration at Agate Beach, Oregon. The company's confidence level soared as it built up operation time with few problems. But the next machine was a heartbreaker.

"We bought the machine as part of our long-range wind energy test program," said Robert L. Scheffler, program director for Southern California Edison. "Alcoa installed it in San Gorgonio, started running it in tests, and it fell down."

When a large Darrieus-type machine—with rotor blades 123 feet tall and 82 feet in diameter—falls down, the machine is essentially destroyed. Alcoa engineers traced the problem to control software that simply wasn't sophisticated enough to handle what happened. As Vosburgh explained the accident, the vertical-axis machine (such machines are not self-starting in the wind) was being started up by a small motor. In the next few seconds, a chance sequence of events ended with wreckage. The microprocessor control system read a wind gust as out-of-limits, and triggered the emergency brake. But the small starter motor had passed control to a large spinup motor, which gave an added push to the blades. The microprocessor registered a conflict between braking and accelerating, and took off the emergency brake, put on the parking brake, and then released it, too. In moments, the conflicting control signals allowed the rotor to spin out of control; bolts snapped; a blade spun away, cutting a guy wire, and Darrieus came tumbling down.



The town of Tisbury, Mass. can get 100 kW of energy for pumping water from a 33-mph wind. This 97-foot-high VAWT, made by Alcoa, is under the technical supervision of Sandia National Laboratories. A gravity water system can often make efficient use of the intermittent character of wind energy. Darrieus machines can use simple construction, employing extruded airfoil blades of uniform cross section for economy.

"The software did not give the emergency brake signal precedence over everything else," Vosburgh explained. "That's a lesson that will now be applied to all of our machines." An improved 500-kilowatt machine will be installed at San Gorgonio. Alcoa will not deliver machines for

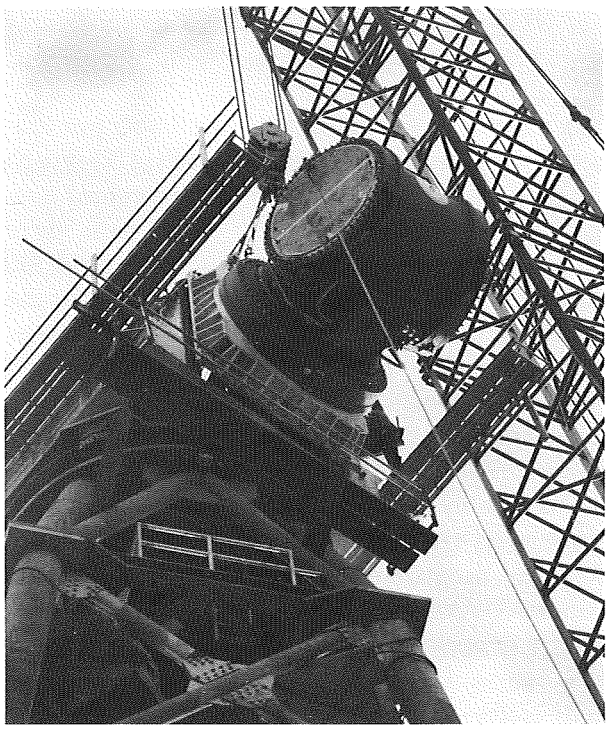
routine commercial applications until the bugs disappear. "We want prolonged testing," Vosburgh said. "As soon as we're convinced the machines are reliable, we will release them for commercial installation. There seems to be no problem selling them."

Wind Farms Limited ordered twenty-two Alcoa machines in 1981 and smaller sales were being negotiated in the Pacific Northwest, Texas, and elsewhere. But deliveries would be unlikely until well into 1982, Vosburgh said. At a minimum, new experience would be needed at San Gorgonio.

With Southern California Edison's aggressively positive attitude toward wind energy, San Gorgonio Pass could become one of the nation's largest wind farms. The company intends to have 360 megawatts of rated wind-turbine power installed before 1990 and expects to average at least 120 megawatts actual power production. "We're into it because we are highly dependent on imported oil," Scheffler revealed. "The price is escalating and it's always subject to embargo.

"Wind has the most near-term promise of anything we've studied. Plus the wind resource is here, with several good sites in our service area. We've got the wind and we've got the motivation to get away from oil."

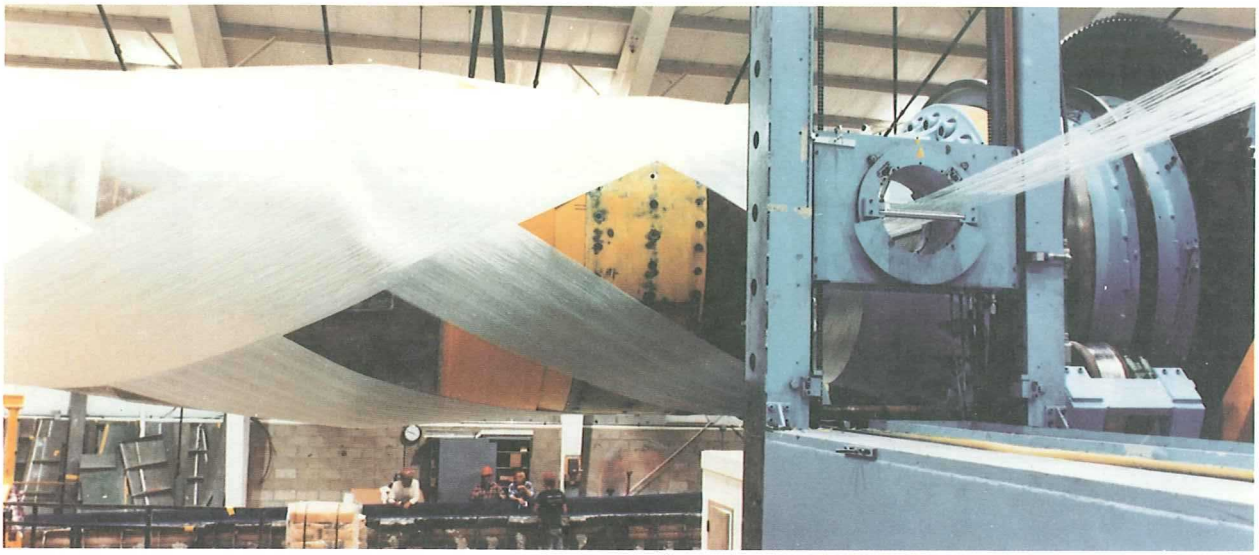
Southern California Edison and Pacific Gas and Electric are not alone in that motivation. Utilities across the country, from Oregon to Texas to Massachusetts are watching wind-turbine development. A few, like Coos Bay, Oregon, have already moved out; Coos Bay installed a 200-kilowatt unit to take advantage of the Oregon coast's high average winds. Another is running on Cuttyhunk Island in Massachusetts. But most utility attention focuses on the next generations of wind turbines, the designs that may make wind energy even more practical, and commercially viable on a national scale.



The hub of the Mod 1 machine in Boone, N.C., ready to receive its blades. Note the slight angle of the mounting faces; the assembled blades will have a 9-deg. cone angle, increasing tower clearance. Hub, rotor, and tower were all relatively rigid on this machine, increasing weights, loads, and costs.

John Sholes, Tom Cahill, Dick Puthoff, and Dick Braasch are key managers for the potential next generation of wind-turbine programs. Their joint goals are to move wind turbines out of the Federal arena and into the private sector. For the early 1980s, that means moving the Federal wind-energy program ahead at the maximum speed allowed by budgetary considerations.

"The Mod 5 concept is to drive the cost of energy to below 4 cents per kilowatt-hour," Cahill said, expanding to the task ahead. "At the same time, we're putting in tougher hardware criteria



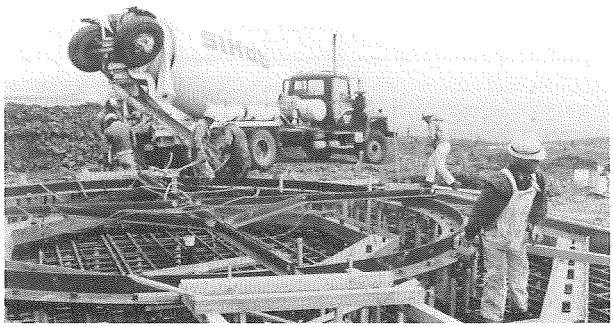
Fiberglass winding begins on a 127-foot Hamilton Standard blade with one of the largest automated winding machines yet built. Work is being done at a company plant near Windsor Locks, Conn. Each blade will weigh about 30 000 pounds. The first pair of blades are scheduled for use on a 3-MW wind turbine in Sweden, and the second set are to be fitted to a 4-MW machine being constructed at Medicine Bow, Wy. Differing mainly in rated output, they will be at least briefly the world's most powerful until the generation still on the drawing boards is engineered, built, and brought on line.

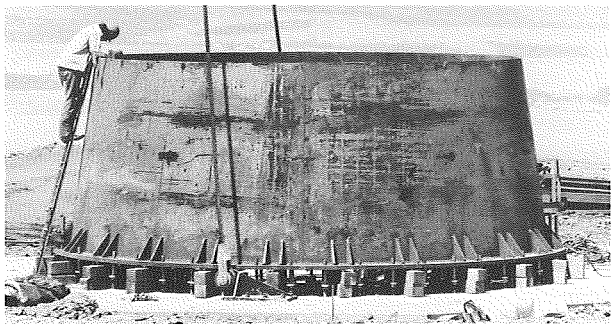
because our main thrust has to be toward electric utility applications.'' General Electric is designing a Mod 5A while Boeing is preparing a Mod 5B. Both companies brought wind-turbine experience to the project, GE from its Mod 1 at Boone, and Boeing from its Mod 2 units at Goodnoe Hills. ''Both designs look good,'' Cahill said in early 1981. ''Boeing's machine looks like a Mod 2 but there are major differences.

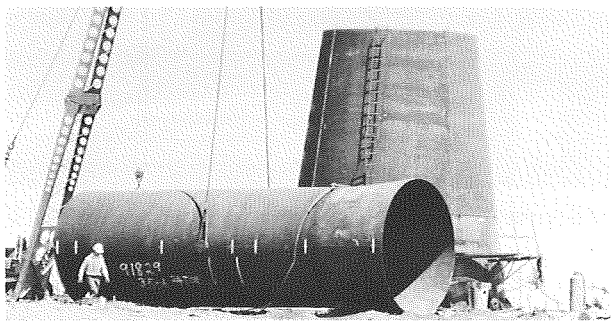
''The 5B is rated at 7 megawatts. The Boeing people are convinced that 420 feet is the best rotor size, but they're looking at different combinations of materials, maybe putting wood or fiberglass or aluminum tips on steel blades.''

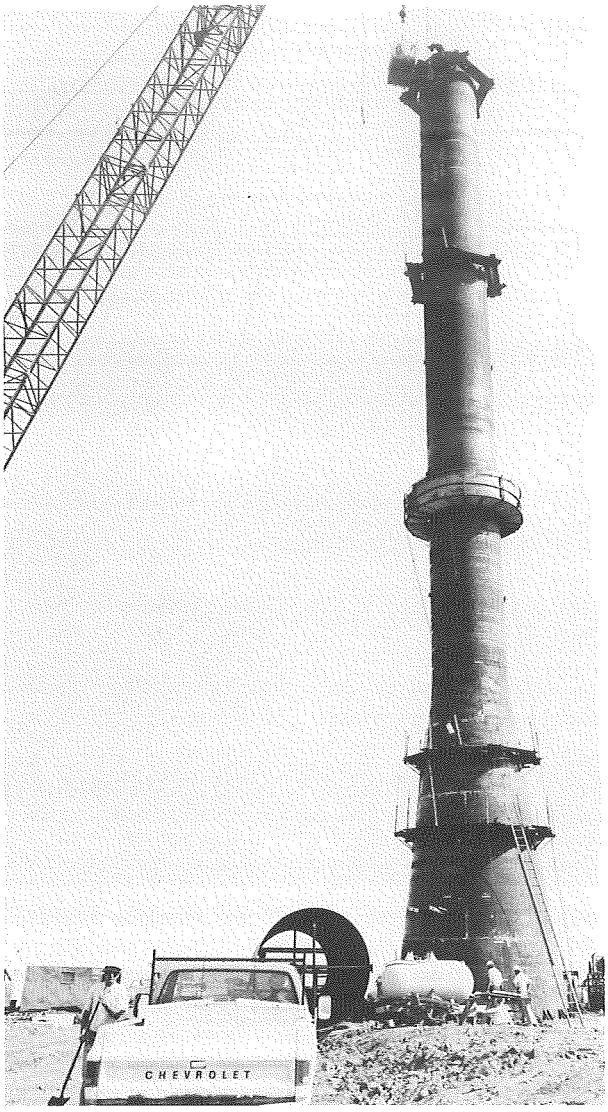
General Electric's Mod 5A is a radical departure from their Mod 1 design. The preliminary design calls for an upwind machine rated at 6 megawatts. After looking at 300-, 400-, and 500-foot blades in materials ranging from steel to fiberglass composites to wood, GE settled on a 400-foot laminated wood epoxy blade. ''The combination of reduced stresses, reduced costs, and reduced weight won out for the wood blade,'' GE's Richard Calef said. Similarities between the two Mod 5 designs include use of a dynamically soft cylindrical tower that can sway up to 4 feet in high winds. That softness reduces stresses throughout the system and avoids much potential trouble from vibration.

But Government funding for the development of these advanced machines is problematical, and neither Mod 5 version may ever get beyond the design stage. Some day, perhaps, private utilities may make the expenditures on their own, although









A relative lightweight at 255 000 pounds, the 192-foot Mod 2 tower is 72 feet taller than the massive truss tower used for Mod 1, but weighs 65 000 pounds less. It is designed to be a "soft" tower, swaying very slightly under stiff gust loading. On its reinforced-concrete foundation go cone sections that taper from 20 feet in diameter at the base to 10 feet in diameter for the uniform part of the structure. A big crane sets each cone and cylinder section in place; the walkways are for welding the circumferential seams and for weld inspection, being removed later. With careful fabrication and skilled steelworkers, this flared shell construction goes up rapidly if wind and weather cooperate. Once up, the principal maintenance needed is periodic inspection and repainting. With the tower complete, the 90-ton nacelle is hoisted up and lowered onto the bearings at the top that allow the turbine to be pointed in any direction by a microprocessor-controlled servo system. Although designed with ample margins of strength, the Mod 2 structure does not strive for the degree of rigidity (with attendant weight and stress) that marked the predecessor Mod 1 machine. The natural frequency of all major elements has been analyzed to avoid accidental resonances that could contribute to vibration problems.

the initial investment would be large. Pacific Gas & Electric will spend nearly $10 million for its Mod 2 unit, including site preparation and installation. Full-scale production of Mod 2 machines ultimately could reduce that by at least 75 percent. Mod 5 machines in full production—in 1986 or 1987 dollars—are likely to be in the same or slightly higher price range, but will be economical and sought after if they reach their COE goals.

Fuel costs as well as tax credits have made wind energy far more attractive to utilities and consumers. The technological strides have brought wind energy close to practicality. Across the nation, utility companies that were indifferent to wind just a few years ago now respond to the concept with

moral support, pro-wind corporate policies, and substantial infusions of private funding.

In 1973, a handful of people, assigned by an energy-conscious nation to tackle the wind, stood at base zero, and shook their heads in awe. The learning began. Tall, sleek towers evolved from spindly open-truss structures. Rotor diameters grew from 125 feet to 200 feet to 300 feet. A trickling 100 kilowatts of electricity grew, then cascaded into 7.5 megawatts. And the sites themselves became encyclopedias of wind-turbine experience, with a place in the history of harvesting the wind.

In 1981, more to the point, each site from Clayton to Culebra, from Block Island to Kahuku Hills continues to produce electricity and experience in equal parts. With private industry joining the parade at San Gorgonio, Solano County, and Kahuku Hills as well, the future of wind energy comes into clearer focus.

In the soft sand of Dockweiler Beach, in the heart of the Los Angeles metropolis, midnight strollers heard the distant rasp of a ship's horn. Running lights on the empty tanker flashed their own salute to the United States. Then with a growling sigh of engines building revolutions toward cruise power, the long ship carved a righthand arc away from shore, toward the distant oil fields of Indonesia or Abu Dhabi. The strolling couples shrugged and walked on. Only dawn commuters along Paseo del Mar noticed that the offshore roads were beautifully empty.

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About the Author

James L. Schefter is a professional writer specializing in engineering topics. He covered his first space mission as a reporter when the Mercury program was drawing to an end in 1963. He has been assigned to most major U.S. space exploration missions in the decades since. He reported on the Gemini and Apollo projects for Time-Life in Houston, has written numerous magazine articles on scientific and engineering subjects, and has closely followed energy technologies in recent years. He succeeded the late Wernher von Braun as consulting editor for space at Popular Science Magazine, and became the magazine's west coast editor in 1978. He has studied the sciences, mass communications, business and national science policy, and holds an MBA degree. He is married to a computer planning expert, and lives in Los Angeles.

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